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Nitrogen Transformation Processes in Constructed Wetlands.

Bachelor Thesis

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Abstract

The primary objective of this work and the research at the "Helmholtz-Zentrum für Umweltforschung" was to gain a deeper understanding of the basically transformation processes, especially for nitrogen species, in constructed wetlands. Therefore two different types of laboratory scale model systems, run with two different artificial wastewaters, had been observed for about 4 months. Data about the situation of three nitrogen species (ammonium, nitrate, nitrite), the physical condition of the pore water and the carbon sources contained by the water had been collected and compared. The present work will provide a summary about the actual knowledge of the microbial processes in constructed wetlands and the general character of such constructions. It will explain the different methods used to gain the data which will be later wards discussed with the aid of the created graphs in the final argumentation.

Directory

1 Introduction

Industrial and domestic wastewaters show partly high concentrations of different organic and inorganic pollutants. The degradation of this mater is imperative necessary not only to provide safe and clean potable water also to prevent irreparable damage from the environment. To meet these conditions several processes of wastewater treatment had been developed.

Constructed wetlands get more and more used for the treatment of municipal and agricultural wastewaters. They reach the efficiency of common sewage plants and are able to remove germs to a high degree. Constructed wetlands also eliminate nutrients like phosphate and nitrogen compounds. The process mainly responsible for the decreasing nitrogen concentration is called denitrification.

This reductive process needs organic wastewater compounds usable by the organisms, what can become a problem. In a process specific time period the nitrogen concentration decreases optimal. Several of the decomposition processes, especially some of the transformation of nitrogen compounds, are in their details still unknown to science.

The research of the transformation processes in two different laboratory scale model systems run with two kinds of artificial wastewater should provide a basic understanding of the nitrogen transformation processes in general. The model systems (already applied in several related experiments) should create a similar milieu for the biocenosis to full-scale systems. Anyway the time stabile, controlled conditions of the laboratory systems are not comparable with full scale systems which are exposed to climate change, a higher influence of the biotic and abiotic environment and the more complex interaction of physical circumstances (i.e. flow conditions). It is not assumed to gain data applicable for full scale constructed wetlands. The nitrogen transformation should have been ob-

served and interpreted in the mean of fundamental research. This happened under (as optimal assumed) conditions controlled in an artificial surrounding.

1.1 Definition; Microbes and Plants Interaction

In the past years the so called "close to nature" processes got popular in different areas of municipal and industrial waste management. The "close to nature" processes share characteristic like there low need for chemicals and their aesthetic, none landscape destroying character. Constructed wetlands are a main representative of these processes. Constructed wetlands in general are planted soil filters for wastewater treatment. They are mainly important for regions with light pollutions and as an economic alternative for the developing countries and emerging markets. Especially for these regions their significant advantage are the low technical requirements. Also they are in the spot as a downstream treatment device for industrial and urban wastewaters [1].

The cleaning effect of these constructions is based on the complex interaction between microbes as the main waste-decomposers and the plants which provide basically an adequate environment for the microbes. The microbes settled in the different biofilms are very specious and complex.

Mainly vascular water and swamp plants like reed, cane and reed mace which can grow also in permanent flooded soils are in use. These plants show a high resistance against pollutions which is based on their special capability of the oxygen input in their rhizosphere [2, 3]. They emit oxygen to the root's surrounding to oxidize dissolved heavy metals and hydrogensulphide [4].

Important to their relationship with the microbes is that they also emit sugars, amino acids, organic acids and dead plant material as different carbon sources. Special attention should be given to the plants while the appearing of seasonal caused climate changes. So decreases the effectively of constructed wetlands

during the winter session in the temperate zone appreciable, but the transformation processes still go on. Dead plant tissue provides a suitable carbon source while the so called Venturi-effect transports oxygen through the dry reed leaves supplying the plant and the microbes in the rhizosphere. Less mentionable is the ability of the plants to accumulate small amounts of pollutants.

1.2 Types of Constructed Wetlands

There are several forms and types of constructed wetlands in use nowadays. An appendage is to differ them by their kind of flow through, the way of cultivation and if they run continuously or discontinuously.

A classification suggested by Stottmeister et al. is the following also shown in figure 1 [1, 5].

- wastewater lagoons with floating plants (A)
- wastewater lagoons with emerse water plants (B)
- bed systems with horizontal subsurface-flow (C)
- bed systems with vertical down-flow (D)

A more in general differentiation is one from the "A Handbook of Constructed Wetlands" it mentions surface flow, subsurface flow wetlands and hybrid constructions.

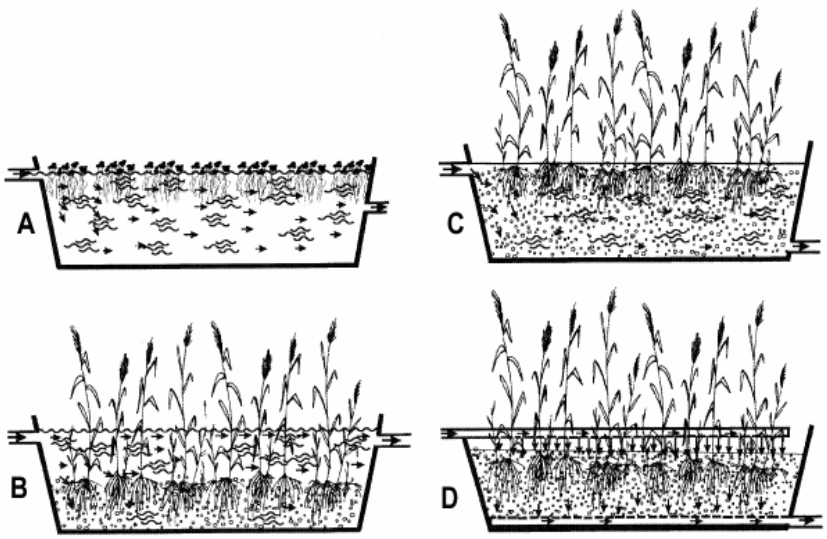


figure 1 *Types of constructed wetlands;*
*wastewater lagoons with floating plants **(A)**; wastewater lagoons with emerse water plants **(B)**; bed systems with horizontal subsurface-flow **(C)**; bed systems with vertical down-flow **(D)**.*
(A-D referred to the text) (Stottmeister et al. (2003))

1.2.1 Surface Flow Wetlands

Constructed wetlands constructed in a way that the water surface lies above the substrate are called surface flow wetlands, sometimes free water surface wetlands or, if they are for mine drainage, aerobic wetlands. These systems provide an aesthetic value like a lagoon and can be a suitable wildlife habitat. These wetlands commonly consists of a shallow basin, soil or other medium to support the roots of vegetation, and a water control structure that maintains the shallow depth of the water.

The aerobic biota takes place in the near surface regions of the wetland while though natural processes the deeper layers and the ground itself is usually anaerobic. Low operating and building costs, a straightforward construction, operation and maintenance are the advantages of these systems.

The higher need for larger land area than other established systems militate against the surface flow wetlands. Typical surface flow wetlands are stormwater wetlands and wetlands built to treat mine drainage and agricultural runoff [7].

1.2.2 Subsurface Flow Wetlands

Subsurface flow wetlands are constructed to hold the water level under the top of the substrate. The effects on the water are comparable to those going on in the groundwater levels and soil associated levels of the water cycle. Subsurface flow wetlands have most frequently been used to reduce 5-day biochemical oxygen demand (BOD_5) from domestic wastewaters. They consist of a sealed basin with a porous substrate where the general waterflow is designed like mentioned in figure 1 either in a horizontal or in a vertical path. The United States of America have the highest number of constructed wetlands with horizontal flow paths. Verticals flow paths are not common. Unlike European systems which use vertical flow paths quite more often [6].

Several names are common for subsurface wetlands. Including vegetated submerged bed, root zone method, microbial rock reed filter, and plant-rock filter systems. This design provides a higher security to its surrounding a reason therefore it is often established in areas acceded by people. On the other hand these systems carry a higher risk of blockage of the soil pores and the hydraulic constraints to transport a special amount of water through the sediment. Therefore these constructions are best suited to wastewaters with relatively low solids concentrations run under relatively uniform flow conditions.

While other systems especially surface flow constructions have problems with environmental terms, especially sub surface wetlands are highly resistant to cold. In addition they have a much lower emission of odour and carry a lower risk to breed pest and, possibly, greater assimilation potential per unit of land area than in surface flow systems. A possible explanation is that the soil (mainly

gravel) particles offers a high specific surface for attached microbial growth and biofilm formation for the treatment, an effect known from activated carbon in several processes. For this reason subsurface wetlands can be constructed in smaller measures then surface flow wetlands.

The mentionable disadvantage of subsurface flow wetlands are their higher construction and maintenance costs. That is why they are often used for smaller flows. Also they are much more complicated to regulate. A number of systems have had problems with clogging and unintended surface flows [7].

1.2.3 Hybrid Systems

Although the good elimination rates in constructed wetlands had been found as adequate, the process got improved by adding different stages to the system. The reductive transformation processes need manifold available organic compounds in the waste water. It is known that under nitrification conditions the concentration of these substances gets to low for further nitrification steps early. A solution for this and similar known problems was the introduction of hybrid or multi-stage-systems. Hybrid systems consist of different cells where different reactions take place. So it got common to recirculate the water in a lagoon or tank, the concentrations of the different carbon sources does not fall this rapidly and in a process specific time period the nitrogen concentration decreases optimal. Also effective wetland treatment of mine drainage may require a sequence of different wetland cells to promote aerobic and anaerobic reactions, as it may the removal of ammonia from agricultural wastewater does [7].

1.3 General Construction and Processes of Constructed Wetlands

In general a constructed wetland consists of the main lagoon and one or several sedimentation tanks. In these tanks the water remains until most of the suspended solids got sedimented. The sedimentation of the suspended solids is important to the maintenance of the reed bed. It prevents a blockage of the soil pores and already gives the biocenosis the chance to start the anaerobic decomposition in a separate ambiance what unburdens the reed bed significant. The process inside the sedimentation tanks is called primary sewage treatment or mechanical pre-treatment.

Conventionally the wetland soil consists of gravel, sand, expanded clay or a composition of different matter. Nowadays a mix of coarse-grained and close-grained material is widely common because these proceeding prevents blockage reliable and does not affect the filter effect. The reed bed is planted with swamp plants here especially *Phragmites australis* proofed its advantages especially its ability to root to a depth from about 1.5 m. Other advantages are the well ratio from root plant mass to aerial mass from 3:1 and a high oxygenation through the roots [1].

1.4 Purification Processes in Constructed Wetlands

The mode of operation of constructed wetlands is based on typical natural microbial, plant-biological and physical processes [8, 9, 10]. They reach a typical removal rate higher then 90% for all pathogens an approximated rate of about 80% for organic compounds [11].

The processes in constructed wetlands can be subdivided in [1]:

- mechanical processes, that means the soil material has a filter effect on the undissolved solids

- biological processes, that means the wastewater compounds are decomposed or at least immobilized by the plants or the microbes

- physical-sorptive processes, what means the accumulation of dissolved substances to the soil material or the roots through adsorption driven by sub-molecular powers like the van der Waals forces or weaker chemical bonds

The fundamental processes decreasing the pollutant concentration in constructed wetlands are the uptake by the plants, the sedimentation of the suspended particles and most important the microbial degradation and conversion processes. Ammonification, nitrification, denitrification, phosphate immobilization, humification, mineralization and dissimilatory sulphate reduction are subject to this rough allocation. These processes are in a sensitive way connected to each other. The total area and geometry of the system, the water amount, organic and hydraulic loading, the total retention time and chemical conditions like the pH value [12], as much as the climatic circumstances influence the efficiency of a wetland.

1.4.1 Plant Uptake and Sedimentation

The growth rate of a plant species defines the potential uptake of pollutant through a plant population. Different uptake rates are caused by different tolerated concentrations in the plant tissue. The ammonium is absorbed directly by the plants where it is further metabolised. The ammonium ion is accumulated to organics so that amino or nucleic acids are generated.

For nitrogen it is assumed that the amount of removed matter by plant biomass lays not over 10% under optimum conditions [13]. All attempts to increase the uptake through the biomass failed or had been at least insignificant [14]. The tests showed that the plant species is the limiting factor for the climax of the

uptake. Generally the potential rate for example is for nitrogen in the range of 0.27– 0.68 g/m² d [15].

Sedimentation is the process of the deposition of matter from liquids or gas by gravity. This physical process is widely used in conventional sewage treatment plants as in constructed wetlands to eliminate suspended matter from wastewater. Commonly this mechanical purification is placed in a special settling basin because the plant cover encumbered the sedimentation and the solids bear a risk to blockage the shallow bed. The reduction of filterable solids in the settling basin can be estimated as about 50% [16, 17].

1.4.2 Mineralization and Huminification

Dead tissue of plants and animals is degraded by reactions pushed by catalytical proteins. When the product of these degradation processes is inorganic the process is called mineralization are the products organic the process is called humification.

Energy-rich organic molecules are decomposed to CO_2, H_2O and other inorganic compounds; the released energy is used by the decomposing organisms. These processes are essential for the ecosystem to survive, increasing amounts of organic matter would prevent organism populations to grow and pollute the environment. They close the metabolism circles and release important elements and molecules usable for all higher organisms [18].

Organic remaining of living tissue and digested remaining of the animalistic alimentation excreted as faeces contain amounts of more complex molecules like sugars, starches, proteins, carbohydrates, lignins, waxes, resins and manifold organic acids. These substances are the most important carbon source for the microbial community needed to build up biomass. Some of them can be de-

composed by the microbial community to simple inorganic substances; some will be splitted to a manifold alloy of so called humic substances.

The destiny of different substances and if they are mineralized (red) or huminized (black), is shown in figure 2.

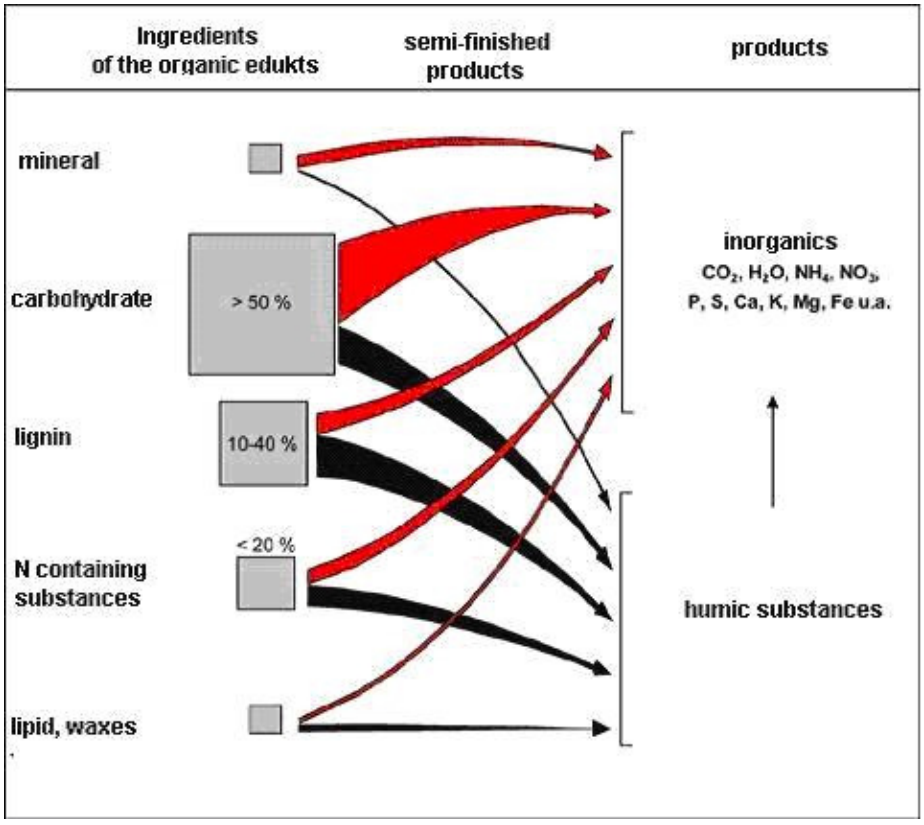


figure 2: *Destiny of different substances in the process of humification and mineralization (translated and changed after SCHROEDER 1992, S. 44) (SCHROEDER 1992, S. 44)*

The biological availability and complexity of these substances determines the time they are decomposed in. The less complex and more available they are - the faster they are degraded by the organisms. Also autolytic processes within the tissues benefit the degradation. The process of organic matter decay starts with the decomposition of sugars and starches, crude proteins, fats, waxes and resins remain relatively unchanged for long times [19]. The humification can take place under aerobic as also under anaerobic conditions. At the beginning stands the hydrolysis, where, through extra cellular enzymes of the involved

microorganisms, high-molecular substances are split into smaller parts. The complete process is still object to research and is not now fully understood.

1.4.3 Nitrification

The oxidation of ammonium into nitrite and further to nitrate is called nitrification. The typical aerobic oxidation of ammonium during the nitrification is a process mainly associated as a pathway of proteobacteria. Other strains of bacteria are necessary for the second step, the oxidation of nitrite into nitrate. This is mainly done by bacteria of the genus *Nitrobacter.* Well known ammonia oxidizing bacteria are the genera *Nitrosomonas* and *Nitrosococcus*. While the oxidation of nitrite is only expressed in proteobacteria the oxidation of ammonium is also used by some archaea. Some publications suggest that even if both bacteria and archaea are present in soils, that archaea are dominant in soils and marine environments [20, 21]. Both steps release the necessary energy coupled to the ATP synthesis for the organisms so survive. The metabolisms of these organisms are distinguished as chemoautotrophs. They use carbon dioxide as their carbon source for growth. Depending on the appearance of the ions the nitrification underlies the pH-value of the solvent and is inhibited by high pH-values.

Another inhibiting factor is the concentration of dissolved oxygen, for the oxidation of ammonium is by the stoichiometry 3.2 g oxygen for every gram of nitrogen and for the oxidation of nitrite 1.4 g of oxygen for every gram of nitrogen necessary [22].

1.4.4 Denitrification

Denitrification is the microbial reduction of nitrate to elementary nitrogen through a series of intermediate gaseous nitrogen oxide products. This respiratory process reduces oxidized forms of nitrogen in response to the oxidation of

an electron donor such as organic matter. In relation to the nitrogen cycle the denitrification completes the circle by giving nitrogen molecules back to the atmosphere. The denitrification takes place under special circumstances in soils and marine environment, in general everywhere where oxygen as a more attractive electron acceptor is missing so that it can be replaced by nitrate species. Due to the high concentration of oxygen in our atmosphere, denitrification only takes place in environments where oxygen consumption exceeds the rate of oxygen supply, such as in some soils and groundwater, wetlands, poorly ventilated corners of the ocean, and in seafloor sediments. Eh values between -50 mV and -300 mV can be an evidence for on going denitrification.

Denitrification generally proceeds through some combination of the following intermediate forms:

$$\mathbf{NO_3^-} \rightarrow \mathbf{NO_2^-} \rightarrow \mathbf{NO} + \mathbf{N_2O} \rightarrow \mathbf{N_2}\ (g)$$

The complete denitrification process can be expressed as a redox reaction:

$$\mathbf{2\ NO_3^- + 10\ e^- + 12\ H^+ \rightarrow N_2 + 6\ H_2O}$$

The process is performed by heterotrophic bacteria, although some autotrophic denitrifiers have also been identified. Denitrifiers are represented in all main phylogenetic groups. Generally several species of bacteria are involved in the complete reduction of nitrate to nitrogen gas, and more than one enzymatic pathway has been identified in the reduction process. Well-known bacteria species are *Paracoccus denitrificans* and various *Pseudomonads* [23].

1.4.5 Other Transformation Processes

The abilities of constructed wetlands are manifold. There are many different transformation processes established by some microbes under the prevailing conditions. These processes underlay special requirements and are insignificant

for the application of constructed wetlands (especially for laboratory scale model systems). In the mean of correctness and completeness they should be mentioned.

The **Anammox** process is the anaerobic ammonium oxidation which enables, through the use of nitrite, the oxidation of ammonium to nitrogen. Because ammonium is combined with nitrite to create clean nitrogen it is just necessary to oxidize only a part of the overall ammonium in the waste water. The Anammox process is almost seven times slower then the aerobic ammonium oxidation, and anammox bacteria have a doubling time of about 10 days [24].

The **nitrogen fixation** is the dumping of elemental nitrogen into the nitrogen cycle. Some bacteria and blue-green alga are able to capture the elemental nitrogen from the air and reduce it to ammonia. The process itself is amazingly energy costly caused by the extremely stable three-point binding of the molecular nitrogen catalysed by specialized enzyme families [25].

Nitrogen assimilation is the uptake of nitrogen by the biomass. Plants take up ammonia directly or though nitrate that is afterwards converted under need of energy to ammonium. The ammonium ions are transformed to carbon compounds to create amino acids, nucleic acids and other nitrogen containing organics [26].

The **ammonification** is responsible for the degradation of organics with nitrogen contingent. Generally it is the mineralization of organics which contain nitrogen. The nitrogen is released as ammonia. A few bacteria, archae and fungi are able to separate the nitrogen from the organics. Hydrolysis of carbamide is an important source of ammonia in urban wastewaters. This reaction is catalysed by the enzyme urease, products are ammonia and carbon dioxide [27].

Phosphate fixation is the storage of phosphorus. It depends on the total amount of removed dissolved inorganic phosphorus by microbial and plant uptake, soil uptake, and the incorporation of organic phosphorus into soil peat.

Also important is the amorphous acid oxalate-extractable aluminium and iron content in the soil [28, 29].

The **sulphate reduction** or desulfurication (for bacteria) is a metabolic pathway used by bacteria and plants. It is the reduction from sulphate to sulphide resp. hydrogen sulphide. The organisms use several organics like acids and elemental hydrogen as reducer. The reactions are exergonic and provide energy for their users. In higher plants even root plastids contain all sulphate reduction enzymes; sulphate reduction takes pre-dominantly place in the leaf chloroplasts [30].

2 Material and Methods

2.1 Planted Fixed Bed Reaktor

The planted-fixed-bed-reactor (PFR) is used for the research of the fundamental transformation processes in constructed wetlands. He is constructed of an open glass tank with a diameter of 28 cm and a height of 30 cm. It is filled with gravel and has after the filling with soil substrate a remaining pore volume for water of about 10 litres. The reactor is at his upper end closed except of five holes for the plants and some valves. The inflow is situated at the top of this cover; the outflow is at the bottom of the glass tank at the deepest point of the construction. The outflow is closed through a sampling valve. The situation inside the reaction chamber is hydrological different from a vertical flow device because in the whole system is a circle flow established driven by a pump. This flow circle provides a macro gradient free reaction chamber with the durable recirculation of the water. Inside the fitting for the circulation are measuring cells installed with a redox electrode, a pH electrode and an electrode for oxygen visible in figure 3. The values of these physical data are recorded continuously through an online computer system. The main task of the PFR is to provide values from so called pulse loading experiments. In such experiments the concentration of pollutants is increased rapidly. These experiments provide especially in comparison to standard continuous experiments interesting findings [31].

For this experiment the systems had been placed in a greenhouse with sensor controlled conditions including air condition and artificial illumination. The systems had been planted with *Juncus effusus* which has proofed as suitable for the laboratory use because it's high tolerance for pollutants and its low height.

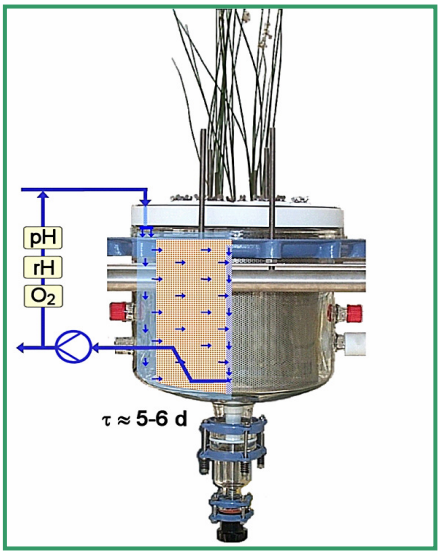


figure 3: *Schematics of the planted-fixed-bed-reactor (PFR) [32]*

2.2 Laboratory-Scale Horizontal Subsurface-Flow Constructed Wetland

The systems used in this work were so called „laboratory-scale horizontal subsurface-flow constructed wetlands" (following wetlands). A sketch of the principal design of such a model is given in figure 4. The dimension of the models is corresponding with the standard laboratory benchmark which provides adequate conditions for research. The beds (wetlands) consist of a tank with a length of one meter and a width of 15 cm; the surface of a bed is for this reason 0.15 m².

The flow direction of the pore water was horizontal situated underneath the soil substrate level. The water surface had no direct contact with the surrounding air. The height of the water was setup to 30 cm; the tank itself was filled to a height of 33 cm with filter substrate (gravel). The grid size of the filter substrate was 2 till 6 millimetres in the diameter, the density 1.665 g/cm³ and the porosity 0.39. The volume remaining after the filling of the tank with gravel for the pore water (soil pore volume) was 14.3 litres.

The solvent for nitrogen ions was stored at point 1 in figure 4, the inflow tank. It flowed underneath the gravel surface and passed the whole gravel bed until it reached the outflow zone (7, figure 4). It was then collected in the outflow tank (5). At the inflow and at the outflow had been areas not filled with gravel this should have enabled a highly constant laminar/streamline flow. These areas had been about 2 cm in the length (6 and 7, figure 4). The pollutant substances had been added between point 2 and 6 through an infusion pump. The whole experiment included four planted gravel beds. At the wetlands like at the PFR models the bulrush (*Juncus effusus; 3, figure 4*) had been used to plant the systems. The wetlands had been operated in separate sensor controlled fully conditioned and lighted greenhouses, to provide highly stable and continuous experiment conditions. The inflow (distilled water with TMS solution, different ions and salts) had been set constant with peristaltic pumps (2, figure 4). Two concentrates which resulted in the artificial wastewater had been added with syringe pumps directly before the inflowing water entered the beds. Sampling happened over sampling lances (comparable to a cannula with a much higher diameter) at fixed points, at the beginning of the experiment by twelve lances in two depths, later wards by 3 in a distance of 0.25 m, 0.5 m and 0.75 m in 15 cm depth and a separated sampling point at the outflow. Values from the first part of the experiment had been transformed (arithmetic mean) to values comparable to those of the second part. The positions of the sampling points (red marks) are shown in figure 4.

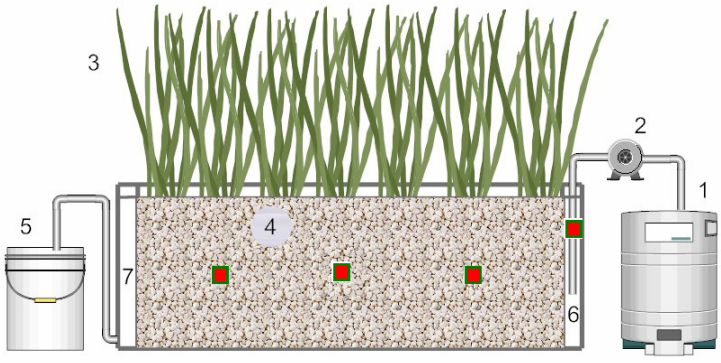


figure 4: *Schematics of an experimental laboratory-scale "wetland".*

2.3 Artificial Wastewater

The artificial wastewater (model wastewater) had an exactly definite composition to not disturb the observation of the fundamental transformation processes by unnecessary disruptive or secondary factors. Two groups of systems, (two laboratory-scale wetlands and one planted-fixed-bed-reactor in each group) had been loaded with the same artificial wastewater.

The composition can be seen in table 2.

Table 1: Composition of the artificial waste waters

Content	Water 1	Water 2
Nitrogen **(mg/L)**	NH_4^+-N:10 and NO_3^-N: 15	NH_4^+-N: 25
SO_4^{2-}-S **(mg/L)**	0.5	0.5
PO_4^{3-} - P **(mg/L)**	5	5
TOC (acetate + benzoate) **(mg/L)**	120	

In praxis the wastewaters had been added in form of two different concentrates for every group. The exact composition can be seen in addendum II.

To create optimal conditions for the microbes and the plants the solution TMS had been added to the wastewaters. TMS contained a wide range of different important trace nutrients (ions). The composition is shown in table 3. TMS had been added in a ratio of one millilitre to one litre of the artificial wastewater.

Table 4: Composition of the Solution TMS (used 1 ml/L at carrier water)

substance	Mass concentration (g/l)
EDTA –Na (Titriplex II)	0,1
$FeSO_4*7H_2O$	0,1
$MnCl_2*2H_2O$	0,08
$CoCl_2*6H_2O$	0,17
$CaCl_2*2H_2O$	0,07
$ZnCl_2$	0,1
$CuCl_2*2H_2O$	0,15
$NiCl_2*6H_2O$	0,03
H_3BO_3	0,01
$Na_2MoO_4*2H_2O$	0,01
$Na_2SeO_3*5H_2O$	0,02
plus 3ml/l concentrated HCL	

2.4 Analysis of The Ions

Some of the important ions had been measured photometrical. For this task established rapid test kits of the company Merck had been used.

Ammonium had been tested with the „Merck-Test-Kit NH4+ Spectroquant®".
Ammonium nitrogen appears partly as ammonium ions and partly as ammonia. The area of the chemical equilibrium is highly corresponding to the pH-value. In strong alkaline solutions the ammonium nitrogen is present nearly entirely as ammonia. The test changes the pH-value of the solution to the high alkaline level. The then dominant ammonia is with contained hypochlorite converted into monochloramine. This joins with substituted phenol to a blue indophenol-derivative. This indophenol-derivative can be determined photometrical. The measuring range of this test lies (dependant from the two useable procedures with different concentrations of the reagents) from 2.0 till 150 mg/l NH_4^+-N and 2.6 -193 mg/l NH_4^+ for a 10 mm cuvette.

Substances which could have corrupted the test had been Fe3+ with apprehensive concentrations from about 25 mg/l and aminophenol species with an apprehensive concentration in the sample form about 10 mg/l [33].

Nitrite had been measured with the "Merck-Test-Kit NO2- Spectroquant®" rapid test kit. Nitrite ions build in acidic solution with sulfanilic acid a diazonium salt. This in turn is able to react with N-(1-naphthyl)-ethylenediamine dihydrochloride and so forms red–violet azo dye. This dye can be measured photometrical. This method had been analogue to the standard US method declared by the EPA. The measuring range had been from the low values determined with a 50 mm cuvette from 0.002 ml/l till the higher concentrations determined with a 10 mm cuvette with 1 mg/l for NO_2^-N, and 3,28 mg/l for NO_2^-N. For the results of the present work a 50 mm cuvette had been used, this enables the rapid test kit to determine smaller concentrations of the nitrite and nitrite nitrogen until 0.002 mg/l. The test kit had been sensitive to concentrations of 1 mg/l of Cr2O22- and Fe2+ which could have altered the results [34].

Nitrate had been measured with the rapid test kit „Merck-Test-Kit DMP NO3- Spectroquant®". Nitrate ions react in sulphuric and phosphoric solution with 2,6-dimethylphenol (DMP) to 4-nitro-2,6-dimethylphenol. This can be determined photometrically. The range of the Test lies between 0.1 mg/l with a 50mm cuvette up to 25 mg/l measured with a 10 mm cuvette for NO_3-N and from 0.4 mg/l up to 110.7 mg/l for NO_3^-. The Test is resistant to the influence of other substances in the sample. 5 mg/l nitrite and 0.2% NaCl can influence the values. For the results of the present work only a 50 mm cuvette has been used, this enables the rapid test kit to determine smaller concentrations down to 0.1 mg/l [35].

During the work values from the nitrate test beyond ca. 30 mg/l had been found as not highly correlative with a standard calibration curve, especially when the 10 mm cuvette had been used and so can be corrupt. This can be seen in figure 5, created with different standard solutions.

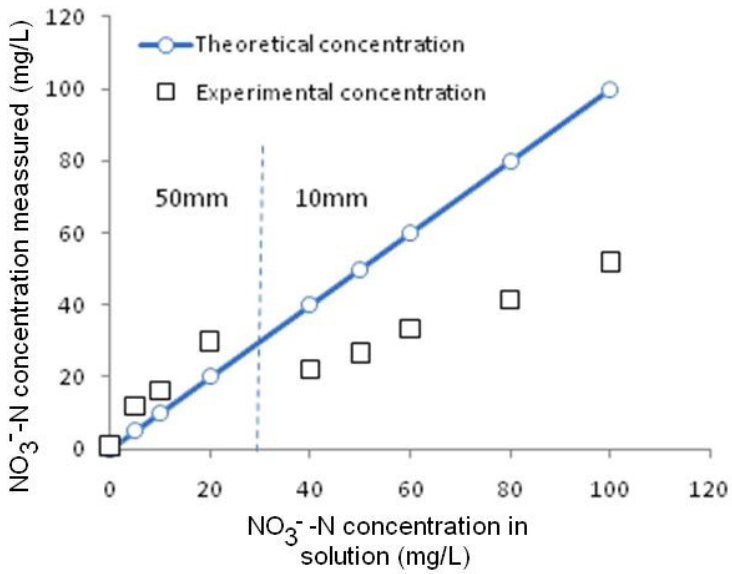


figure 5: *Accuracy test on the Merck Nitrate rapid test kit.*

Phosphate had been tested frequently to monitor the conditions of the systems. To determine phosphate the rapid test "Merck-Test-Kit P-Spectroquant®" had been used. The test had been analogous to the EPA US standard methods and ISO. In sulphuric acid solution orthophosphate ions react with molybdate ions to form molybdophosphoric acid. Ascorbic acid reduces this phospomolydbenum blue (PMB) that had been determined photometrically. The test kit had a range from 1 – 100 mg/l PO_4-P, 3 - 307 mg/l PO_4^{3-}. Phosphate species had been determined using a 10 mm-cuvette. AsO43- ions can reduce the reliability of the values [36].

For all tests the photometer from Merck "Spectroquant Nova 60" had been used. The device uses internal calibration curves and programs containing the wave length for every test, these programs are called automatically by a program bar which is part of the rapid test kits. A blank was not necessary.

2.5 Analysis of the Physical Parameters

Eh and pH had been measured immediately when samples had been taken. Therefore a construction of two measuring cells driven by a peristaltic pump (Watson Marlow 205U) had been connected to the sample point/lances in the wetlands (see fig. 6). The electrodes SenTix® ORP103 648 (Eh) and SenTix® 41 (pH) had been in use. Profi Line pH 197i (pH) and pH 340 (Eh) from WTW had been used as transducer/electrical measuring device.

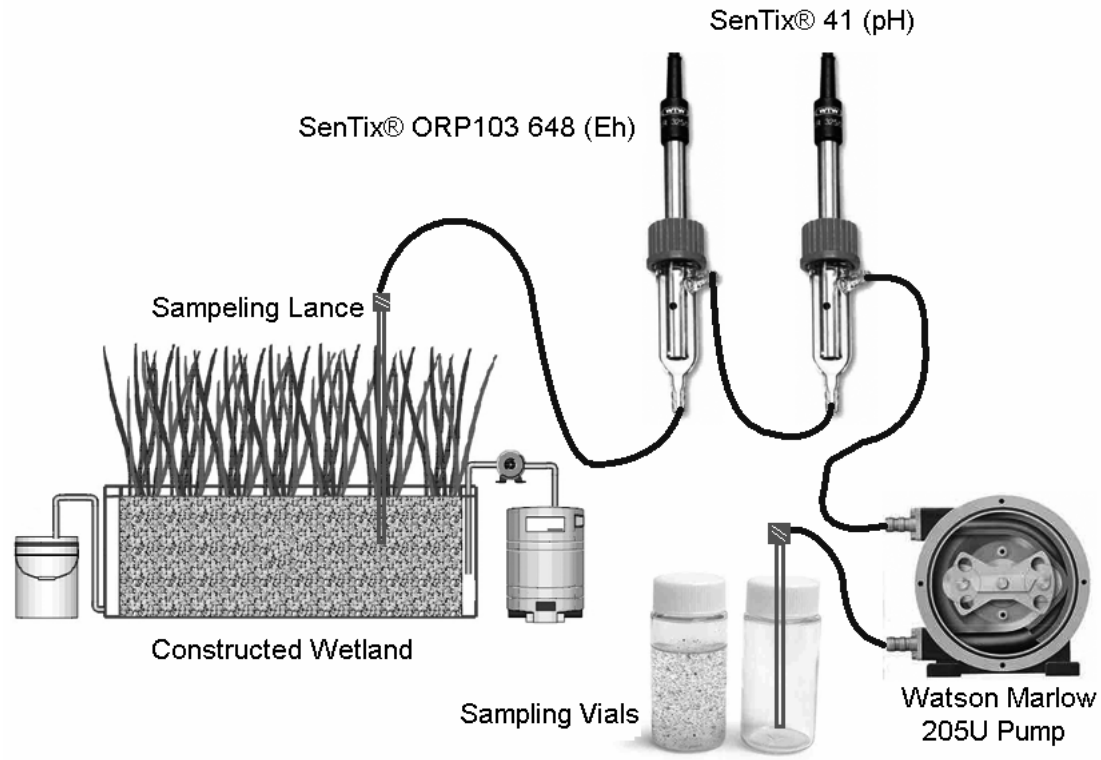


figure 6: *Schematics of the hardware arrangement to take samples during the experiment.*

2.6 Water mass balance

The water mass balance had been a tool to provide a possibility to calculate from the concentrations and the water inflow the pollution loads in the wastewater and the systems. The plants took up parts of the water, also some water evaporates to the surrounding air, the ions stay back and the concentration enriches.

The loss of water had to be considered. A scale had been used to determine the weight of the inflow and outflow tanks, after an specific time period the tanks had been weighted again. So the inflow rate (ml/min) and the water loss could be calculated. It had been necessary to control the inflow rate to hold the load constant over the running time of the experiment.

3 Results and Discussion

It had been necessary to compare the load of the different nitrogen species to be able to make a statement of their general function. Therefore the concentrations had to be calculated to loads; in this process the water loss had been important. In chapter one the concentration changes of the different nitrogen species had been discussed under consideration of the water loss, dependant on time. In the following the change of the different parameters along the length of the system had been analyzed.

During the experiment the physical parameters of the pore water and the concentration of the nitrogen species had been observed for 90 days. The first samples had been taken around the 23rd of March. Considered had been all values within the time from 22.3.2010 to 11.6.2010 for the reactors and wetlands. In the week of the 22nd March it had not been possible to take samples from wetland 3, comparisons and referents with wetland 3 in this time had not been created. During the experiment, at the 55th day the inflow rate of the wetlands had been increased from 2.97 l/d to 4.17 l/d on average. The calculated retention time of the water in the filter substrate (without considering the water loss) had been 3.575 d for the wetlands and 2.5 d for the reactors. The reactors inflow rate had been 2.89 l/d on average for the first until the 42nd day and got increased to 4.06 l/d on average. The average inflow load for ammonium had been about 36.28 mg/d for group 1 wetlands (1, 2) and 31.37 mg/d for reactor 3; 89.15 mg/d for the wetlands 3 and 4 (group 2) and for reactor 4 with 77.87 mg/d.

3.1 Effectiveness of the Nitrogen Removal

The water as the solvent for the nitrogen compounds and the solvent removal by evaporation and transpiration had determined the concentration of the ammonium, nitrate and nitrite directly. The transpiration had been in turn depend-

ant on the plant activity which could have been assumed as correlating with the intensity of solar radiation. The solar radiation increased during the experiment's running time from the winter and spring months to the summer season in June. Never mind the change of radiation the water loss stayed for 90 days almost constant. Transpiration seemed to be controllable through artificial radiation in the greenhouse. Evaporation could have been assumed as constant under the artificial conditions in the greenhouse, the constant values of the 90 day experiments has confirmed this. The controlling of the environmental conditions in the greenhouse could be assumed as effective referred to the water loss. It could be seen in the diagrams shown in figure 7 that the wetlands (HSFCW 1-4) reacted immediately on the changed inflow rate, but the water loss (the distance between the curves) stayed on average constant at about 2.57 L/d with both different inflow rates.

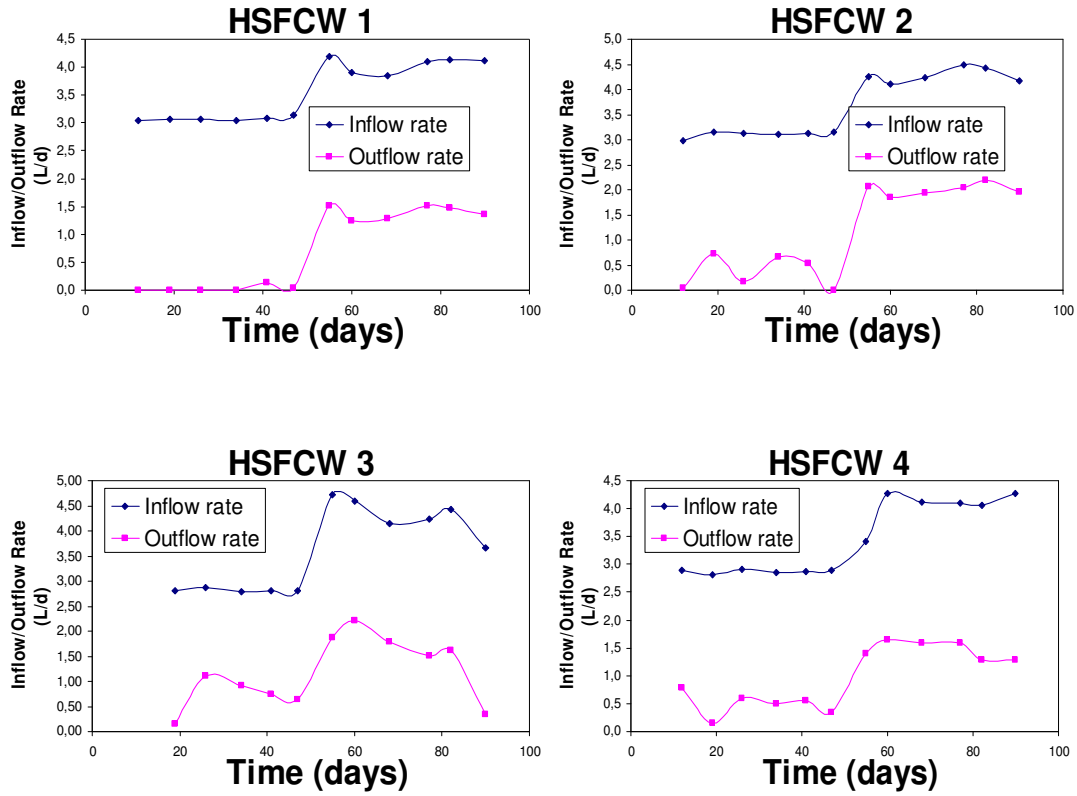


figure 7: *Water inflow and outflow rate for the wetlands 1-4 (HSFCW 1-4). Inflow- and outflow rate means the specifically amount of water per day that enters and leaves the system.*

Figure 8 showed that the water loss from the reactors was less. On average the water loss had been 0.44 L/d it means only 17,1 % of the water loss of the wetlands caused by the smaller surface area and volume, less plants and the cover plate of the reactors.

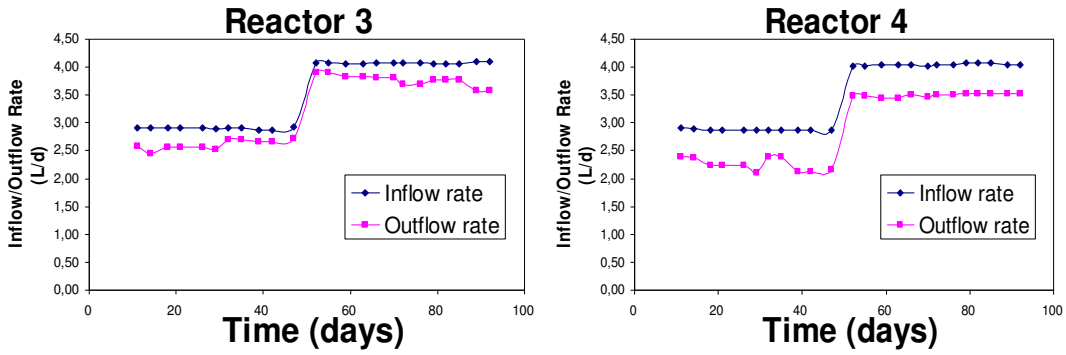
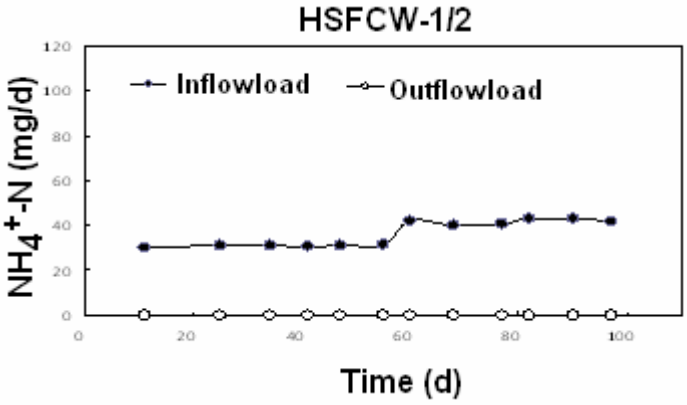


figure 8: *Water inflow and outflow rate of reactors 3 and 4*

3.1.1 Ammonium

In the figure 9 (a) and (b) had been the inflow and the outflow load of the wetlands shown. The wetlands 1 and 2 (HSFCW 1/2) and the wetlands 3 and 4 (HSFCW 3/4) had been calculated on the average. The removal of ammonium-nitrogen had been almost complete. For the wetlands 1 and 2 an average outflow load of 0.00 mg/d and for the wetlands 3 and 4 with more than double inflow load also an average low outflow load of 0.60 mg/d had been determined. This equated to a complete ammonium removal for the wetlands 1 and 2 and a removal of about 99.3 % for the wetlands 3 and 4. The outflow load had been strictly around zero and just increased with the rise of the inflow load in the wetlands 2 and 4 around the 55th day to about approximately 1.5 % of the inflow load. After two weeks the wetlands had become fully used to the higher load and reached again a removal of about 100 %. In the wetlands 1 and 2 the removal was constantly complete.

(a)



(b)

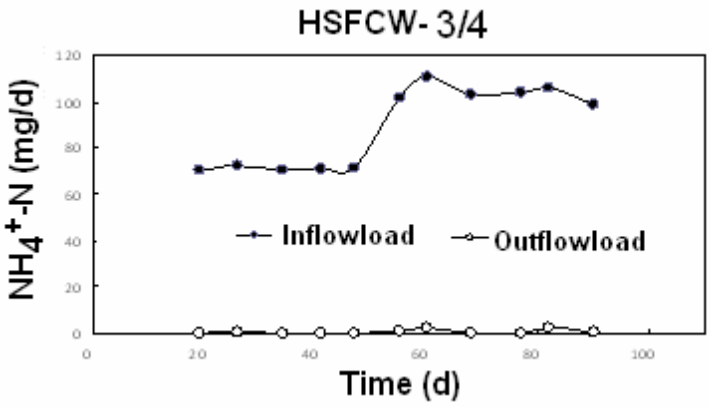
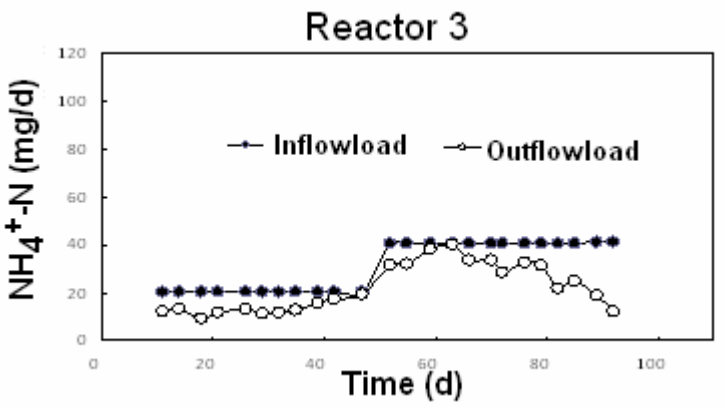


figure 9: *Ammonium-nitrogen inflow and outflow loads for the wetlands 1-2 (HSFCW 1-2) (a); and wetlands 3-4 (HSFCW 3-4) (b); math average of every group.*

Figure 10 shows the in- and outflow loads of the reactors 3 (a) and 4 (b). There had been some irregularities after the increase of the inflow rate. Never mind the proportion between the inflow and the outflow load adjusted stable after some time. Reactor 4 showed after the increase almost the same outflow like inflow load; the biota adjusted in the next 3 weeks and reached again a similar removal rate after a last peak at the 76th day. Reactor 3 needed, with lower absolute values for the removal per week, the same time to reach an even higher removal rate then before the inflow increase (on average 34.7 % in the first 11 weeks, after 8 weeks accustom time 52.2 % on average a rising over 4 weeks). Reactor 3 had reached summed up higher removal rates than reactor 4; reactor 4 had a higher quantitative/absolute removal (in average 9.5 mg/d

for reactor 3 and 19.0 for reactor 4). The biota in reactor 3 transformed 30.4 % of the inflowing ammonium, in reactor 4 24.4 %.

(a)



(b)

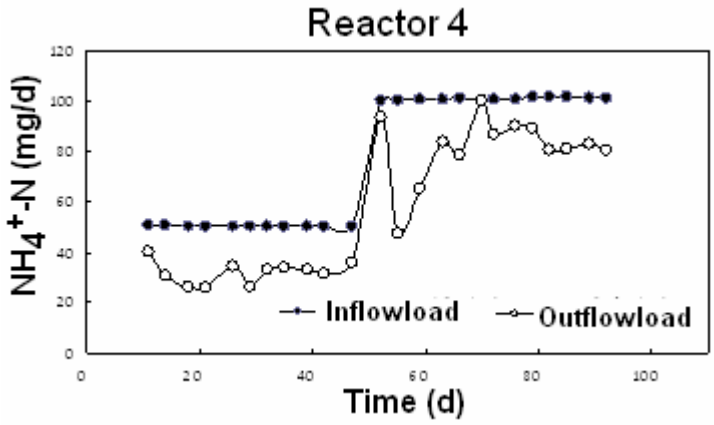


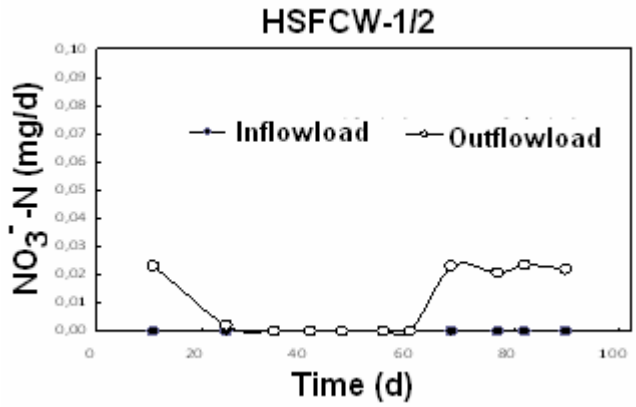
figure 10: *Ammonium-nitrogen inflow and outflow loads for the reactor 3 (a); and reactor 4 (b)*

To sum up the reactors had been better able to handle smaller ammonium amounts with some nitrate than the same stoichiometrical amount of nitrogen in form of ammonium only. The removal rate of the wetlands had been about 3.57 times higher than the ones of the reactors. A probable reason could have been the longer retention time. The wetlands and reactors from every group considered together, the systems run with ammonium and nitrate showed a 4.85 % higher removal rate. The differences had been more distinct for the reactors.

3.1.2 Nitrite

Nitrite had been the product of an uncompleted nitrification and was under oxic conditions fast further metabolized. So, the nitrite of the porewater had been the product of the transformation of other nitrogen species. The graphs in figure 11 showed the nitrite loads for the wetlands 1 and 2 (a) and 3 and 4 (b).

(a)



(b)

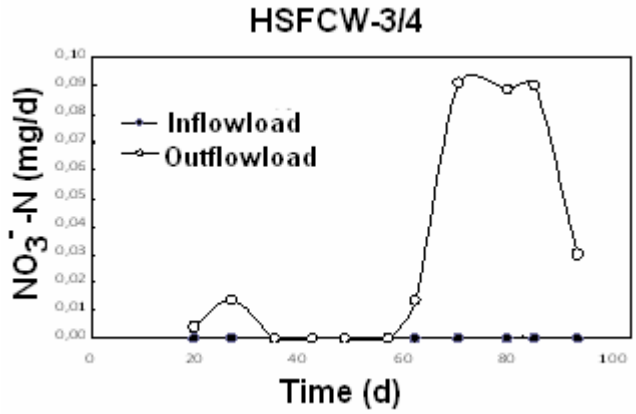


figure 11: *Nitrite-nitrogen inflow and outflow loads for the wetlands 1-2 (HSFCW 1-2) (a) and wetlands 3-4 (HSFCW 3-4) (b), math average of every group.*

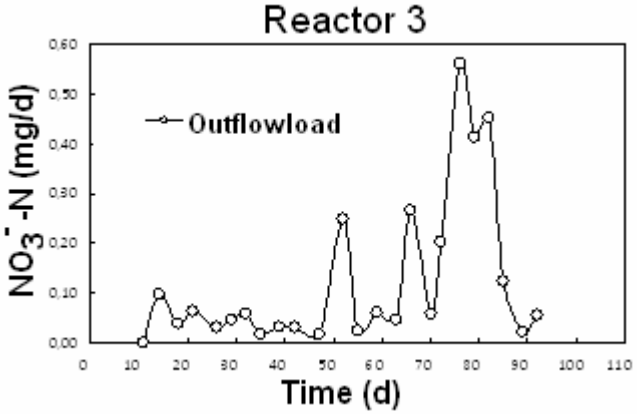
At the beginning of the experiments the nitrite outflow load in all wetlands had been already low and went down to almost zero about the 26th day. It could be assumed that the conditions for the further nitrification adapt later than the ones for the first step. The increase of the nitrite load in the wetlands 3 and 4

could be seen as a laq-phase for ammonium transforming bacteria as the falling loads could be seen as a laq-phase for nitrite transforming bacteria.

Around the 60th day the loads of nitrite in the wetlands had increased. This corresponded with the rise of the inflow rates around the 55th day. While the load of nitrite in the wetlands 1 and 2 adapted stable after the rise of the inflow rate the biocenosis of wetland 3 and 4 had been first able to decrease the load over the next 35 days again. From the transformed ammonium or reduced nitrate in wetland 1 and 2 0.026 % remained as nitrite and was not further oxidized or reduced. For wetland 3 and 4 this value was about 0.022 %.

The reactors reacted to the increase of the inflow rate with more nitrite in the outflow as the wetlands did, seen in figure 12.

(a)



(b)

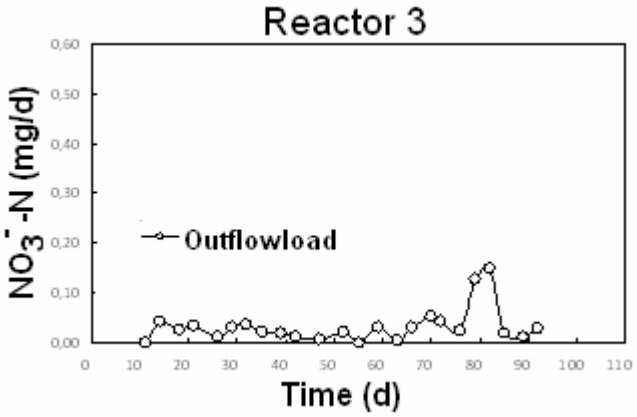


figure 12: *Nitrite-nitrogen outflow loads for the reactor 3 (a); and 4 (b).*

In reactor 3 contrary to the wetlands appeared higher values than in reactor 4 and the other way round after the increase of the inflow. Values around this time had been fluctuating in reactor 3.

While Eh had been more or less constant in nearly all systems the redox potential in reactor 3 strongly increased for 30 days (as the outflow nitrate load did (figure 14)) after the inflow rate rise, shown in figure 13. In this time the Eh of reactor 3 reached the ones of its group wetlands. At the end of the experiment the pore water reached again low redox values suitable for denitrification. A this high redox potential had been never observed for the reactors at any other time of the experiment. Eh stayed strictly positive for all wetlands in the range of 60 – 470 mV in all groups while the reactors most of the time had values underneath zero. After the increase of the inflow; reducing transformations in reactor 3 had been stopped while in reactor 4 the denitrification still had been active. Reactor 3 reached in this time not such a nitrification rate as the wetlands did.

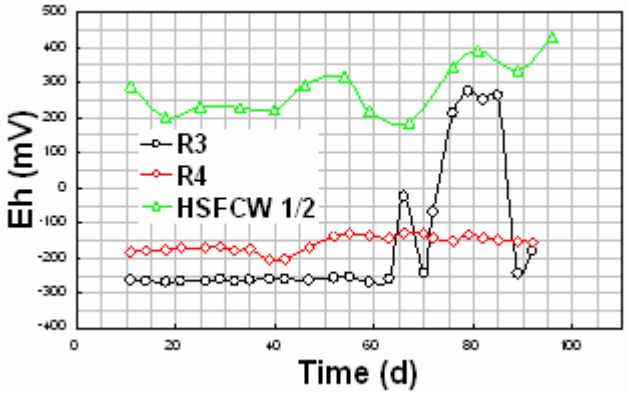
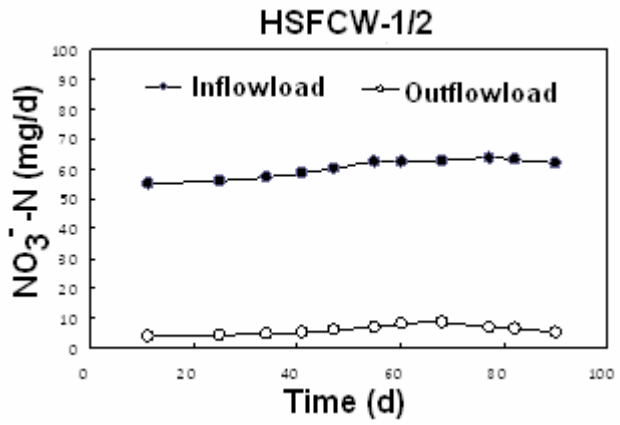


figure 13: *Outflow Eh of reactor 3 (NH_4^++NO_3^- load), reactor 4 (NH_4^+ load) and the average values of wetlands 1 and 2 (NH_4^++NO_3^- load).*

3.1.3 Nitrate

Nitrate had been the final product of the nitrification and could have been reduced through nitrate reduction processes. The most important reduction process had been the denitrification. Denitrification is an anaerobic process situated in oxygen free zones of the wetland. Aerob denitrifikation is also known to science according Kadlec and Knight (1996) but its effect had been less important, almost insignificant [8]. The inflow and outflow loads on average for every group of the experiment had been shown in figure 14.

(a)



(b)

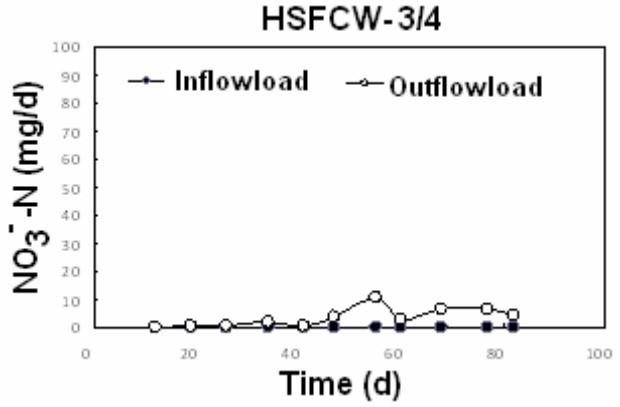


figure 14: *Average inflow and outflow loads of the wetlands 1/2 (HSFCW 1-2) (a); and wetlands 3/4 (HSFCW 3-4) (b) nitrate-nitrogen.*

The wetlands 1 and 2 removed the nitrogen to a big extent (fig. 14 a). The biota had been also able to remove/fixate the nitrate. The in the wetlands measured redox potential showed strict positive dominant oxidative processes. Nev-

ertheless, the redox potential of the inflow of the first wetlands had been relatively low during the first five weeks; shown in figure 15; with 153.28 mV on average at the inflow. In comparison the Eh of the inflow for the last five weeks had been double as high as the ones from the beginning with 303.3mV on average. All outflow values had been dimensional comparable (first 5 weeks: 235.6mV; last 5 weeks: 296.2 mV). Chapter 3.2 will show that the main nitrate reduction proceeded in the inflow region of the wetlands. In these weeks also the effluent nitrate load had rose. Higher activity of the denitrifiers could have been assumed. However coherence had not been attestable because this rise also corresponds to the rise of the inflow rate/load.

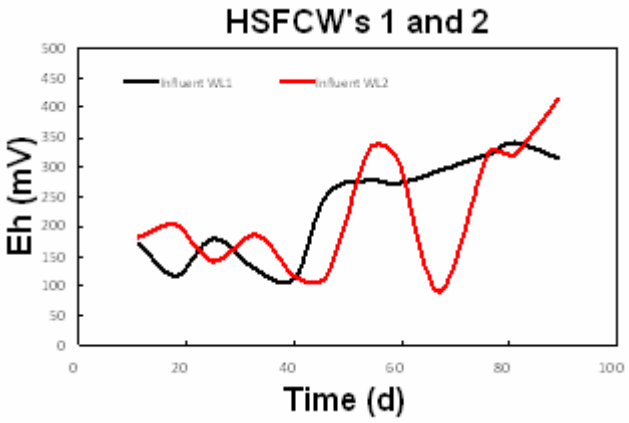


figure 15: *Graph for inflow Eh for wetland 1 (black) and wetland 2 (red).*

The average nitrate inflow load had been 54.4 mg/d and the wetlands reached an outflow load of 3.6 mg/d on average. This confirmed an overall removal rate of 93.5 % for 90 days.

The wetlands 3 and 4 run with no nitrate in the inflowing water. The systems had build up nitrate while the nitrification. The average outflow load had been determined to 3.44 mg/d. This value had been close to the average outflow of the wetlands 1 and 2 (3.6 mg/d). Nitrate concentration in the outflow seemed to be akin to an absolute term for systems with the same technical realization.

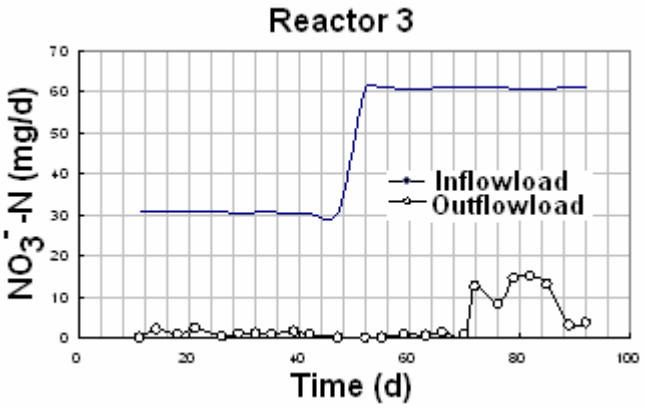
The feed nitrogen species had no or at least just a weak influence on the total resulting nitrogen load of the wetlands. Nitrate reducing processes could have been advantaged when the loads surpass 3.5 mg/d so that all wetlands had been able to reach an approximately outflow load from 3.5 mg/d even if the wetlands 1 and 2 already had nitrate in their inflow.

The systems reacted with a higher outflow load on the increased inflow rate. Until the 55th day the outflow load had been 0.74 mg/d on average; after this day 5.77 mg/d; about 7.8 times higher. In the pore water remained 3.37 mg/d on average. With 88.51 mg/d NH_4^+-N containing 77.45 mg/d N - 1.6 % of this nitrogen remained as nitrate in the porewater (3.37 mg nitrate-nitrogen contains 1.24 mg nitrogen).

Also the reactors had shown an analogue behaviour about the final nitrate load visible in figure 16. Whether nitrate had been contained in the inflow or not the outflow loads had been on average 3.59 mg/d (R3) and 2.35 mg/d (R4).

The differences between the both systems stayed stable after the rise of the inflow rate. At the beginning of the experiment they had been 0.95 mg/d and 0.57 mg/d after the inflow rise 5.64 mg/d and 3.58 mg/d, these resulted in a ratio between the systems from 1.53 in the beginning and 1.46 after the inflow rise. After the 55th day reactor 3 had raised its outflow rate about the factor 3.78 to 5.64 mg/d and reactor 4 about 4.12 to 3.85 mg/d. The outflow loads had shown noticeable changes from the inflow rise about 17 days later in both systems. Reactor 3 had an elimination of 92.6 % close to the on of the wetlands feed with the same artificial wastewater (wetland 3 and 4). In reactor 4 1.3 % of the inlet ammonium was over 90 days present as nitrate in the outflow. The wetlands 3 and 4 showed 20.67 % more of the ammonium-nitrogen as nitrate-nitrogen.

(a)



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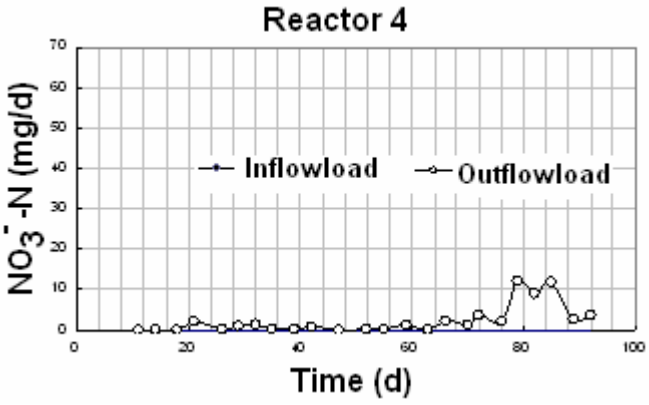

figure 16: *Nitrite-nitrogen outflow loads of the reactor 3 (a); and reactor 4 (b).*

The wetlands 1 and 2 had been feed with an average ammonium-nitrogen load of about 36.3 mg/d and a nitrate-nitrogen load of about 54.4 mg/d. This means an average elemental nitrogen load of 45.1 g/d. Wetland 3 and 4 had been feed with an average ammonium load of 89.15 mg/d which corresponds an elemental nitrogen amount of 78.01 mg/d. The wetlands 1 and 2 carried an elemental nitrogen load of 1.31 mg/d bound in nitrate-nitrogen in the outflow. The wetlands 3 and 4 carried 0.525 mg/d bound in ammonium-nitrogen in the outflow (nitrate-nitrogen outflow had been insignificant low and was not considered). This had been to a total nitrogen elimination of 92.11 % for the wetlands 1 and 2; and a total nitrogen elimination of 97.96 % for the wetlands 3 and 4. The higher elimination of the wetlands 3 and 4 could be explained through a maybe higher plant uptake. Plants favour the uptake of ammonium-

nitrogen to the uptake of nitrate according Kadlec and Knight (1996) [8]. If the plants in the wetlands 3 and 4 had been stimulated through the high ammonium-nitrogen load to take up more ammonium than the wetlands 1 and 2 than this would have explained the higher total nitrogen load.

The reactor 3 had been feed with 109.31 mg/d nitrogen and released 31.48 mg/d (30.21 mg as ammonium-nitrogen, 1.27 as nitrate-nitrogen). It had been able to eliminate 71.10 % of the total nitrogen from the water. Reactor 4 had been run with 155.76 mg/d total nitrogen in form of ammonium-nitrogen and released 122.75 mg/d (121.05 mg/d ammonium-nitrogen; 0.85 mg/d nitrate-nitrogen) this equated an elimination of about 21.19 % for total nitrogen. Reactor 4 released some nitrate even if the redox potential showed dominance of reducing processes shown in figure 13. The in comparison to reactor 3 lower pH value indicated a dynamical regulation of reducing and oxidizing processes (only denitrification should cause higher pH values); visible in figure 17. The irregularities of the pH-value fit in time with the ones of the ammonium load.

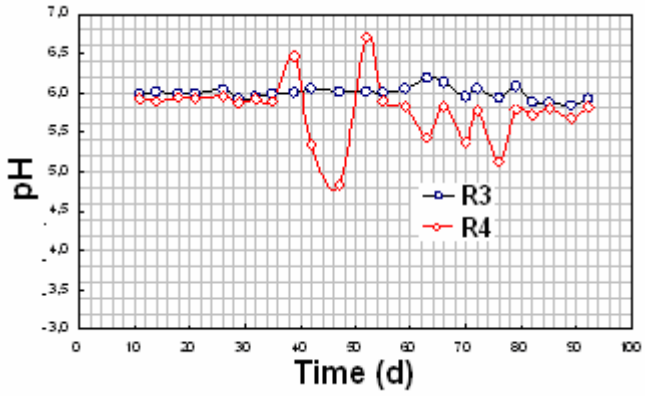

figure 17: *pH-Values for reactor 3 (black) and reactor 4 (red).*

The nitrate had been the product of the nitrification, the high ammonium concentration and the constant low Eh values indicate a slightly inhibited nitrification.

The total nitrogen removal should be seen as the result of denitrification, some in the sum insignificant other nitrate reduction processes and the fixation of nitrogen in plants and microbial biomass. The plants and microbes as a sink could release the bound nitrogen again after their tissue dead (just a small amount is stored after decay in the soil). As the final step of a complete denitrification the systems released the eliminated nitrogen as N_2O or elemental nitrogen to the surrounding.

3.2 Physicochemical Analysis: Milieu Developement

Constructed wetlands provided efficient elimination rates because of their ability to contain different redox conditions in their system. Reducing and oxidizing processes can be established. The laboratory scale constructed wetlands had been analyzed regarding their different physical and chemical gradients and the there placed transformation processes. Also the loads of the nitrogen species along the length (flow path) of the wetland had been shown in figure 18.

For ammonium and nitrate the main elimination processes took place in the first 0.2 meters of the wetlands. After 0.25 m in the filter substrate 86.9 % of the ammonium had been eliminated from the porewater. 88.06 % of the nitrate had been already eliminated from the water after 0.25 m flow length. The average load of nitrite of 0.017 mg/d had also been reached after this 0.25 m.

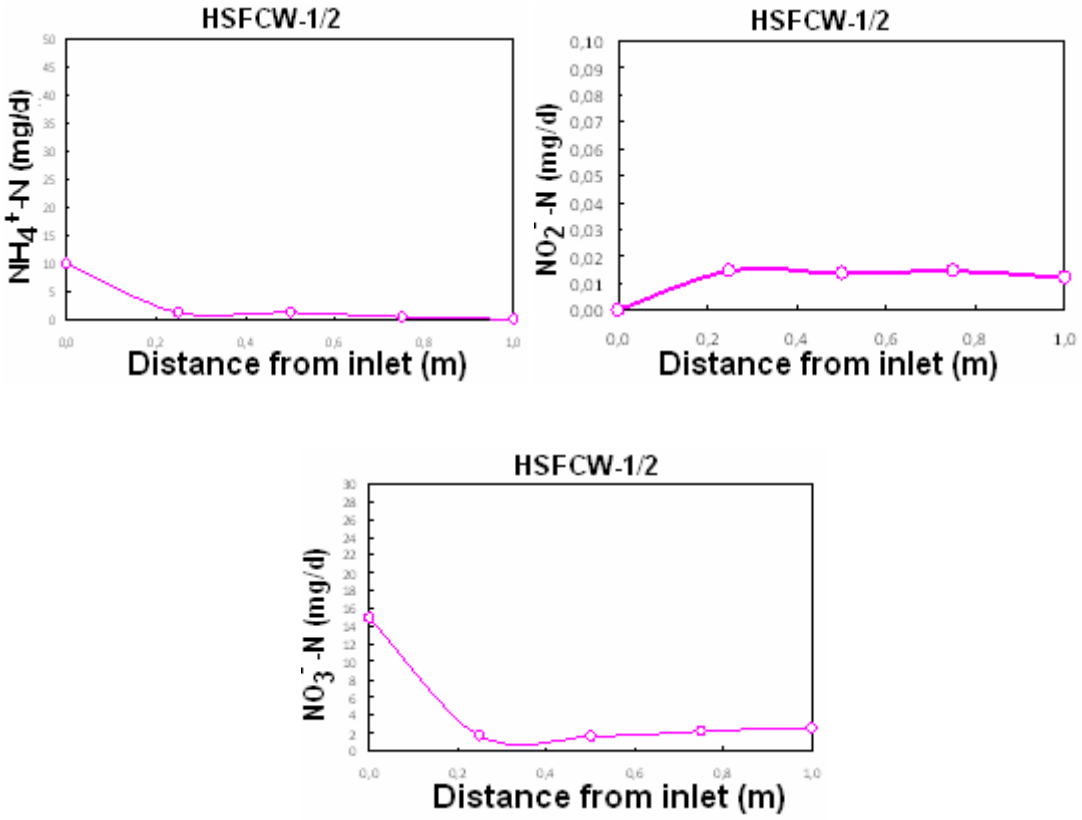

figure 18: *Mean loads of ammonium, nitrite and nitrate over the length of the wetlands 1-2 (HSFCW 1-2)*

The graphs of the physical parameters (redox potential and pH) visible in figure 19 had shown no irregularities. pH had been constant close to the neutral value and Eh had been strictly positive. Also around the biological most active part of the wetlands (the first 25 cm) the values had been stable. Nitrification and denitrification favour different physical conditions. Ongoing nitrification raises the pH, denitrification decreases the value. Plant uptake of nitrate should be assumed as less favoured in the presence of ammonium. The stable pH indicated a dynamical regulation of both processes, even if the Eh is strictly positive reducing areas in the micro gradients could been assumed to explain the nitrate loss. Oxidizing activity could have been so high that dissolved oxygen had been consumed in some areas, resulting in a reductive milieu.

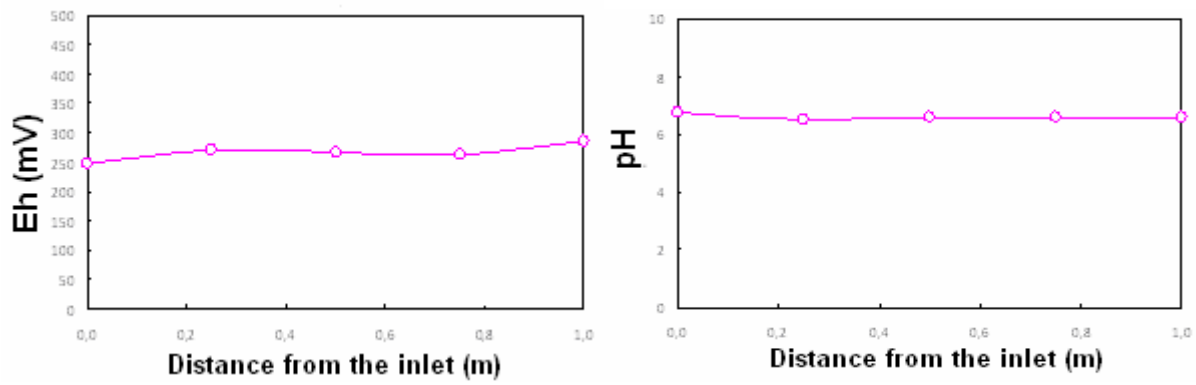

figure 19: *Mean Eh and pH over the length (flow path) of the wetlands 1-2 (HSFCW 1-2)*

The concentration of the nitrogen species in different zones by length of the wetlands 3 and 4 on average had been shown in figure 20. The systems needed much more of their length to decrease the ammonium load to the same extent as the first wetlands 1 and 2. First at the distance of 0.8 m from the inlet the ammonium had been decreased to 94.32 %, at the first 25 cm just to 43.0 %. This conformed an ammonium amount from 10.75 mg/L. Wetlands 1 and 2 had been able to decrease the ammonium amount to about 8.69 mg/L, so the wetlands 3 and 4 have had a higher absolute removal for ammonium even if the relative removal had been lower than the one of the wetlands 1 and 2.

Wetland 3 and 4 had had insignificant higher nitrite concentrations of about 0.00014 mg/L. Like in the wetlands 1 and 2 the nitrite concentration rose along the first 0.25 cm of the flow path. Other than in the wetlands 1 and 2 it had rose higher to 0.01755 mg/l (wetland 1 and 2 reached 0.01658) and then loss nitrite again at a length of about 0.6 m. The same effect had appeared weaker in wetland 1 and 2. The end concentrations had been comparable. Nitrite oxidizing bacteria seem to had been populated in a higher number more far away from the inlet.

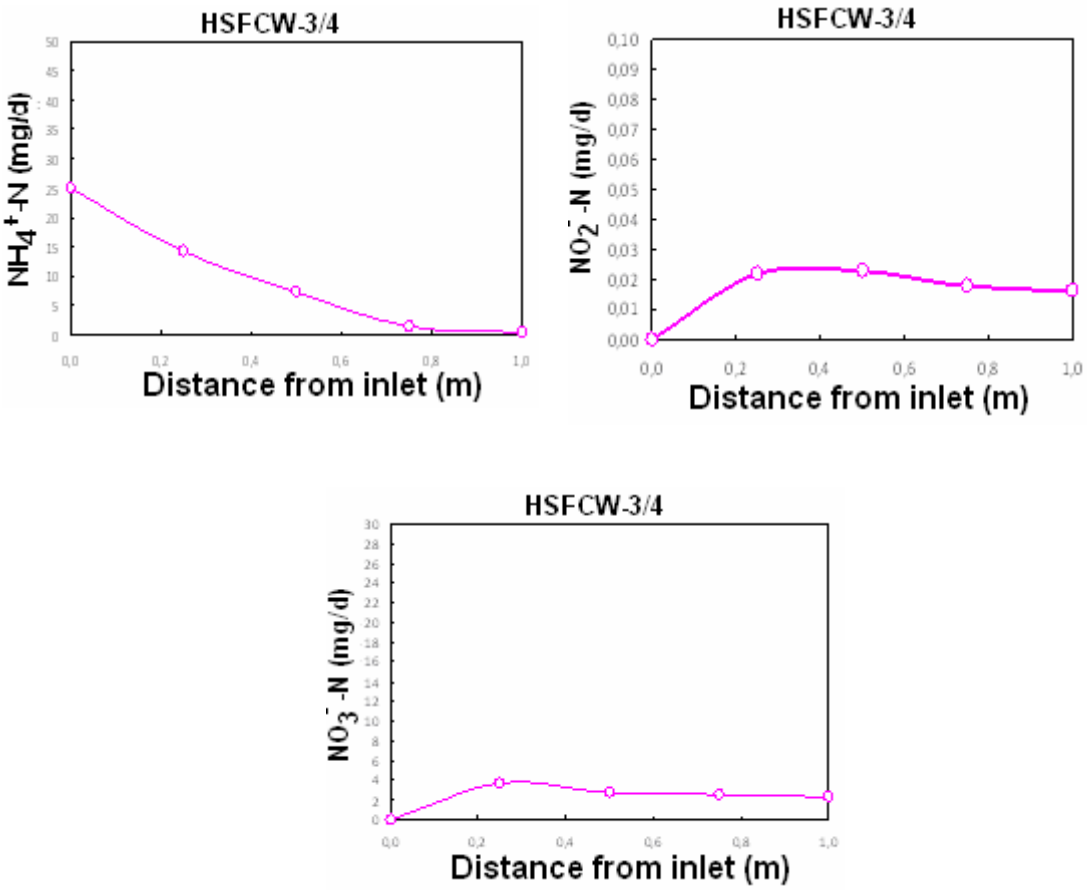

figure 20: *Mean concentrations of the nitrogen species in the porewater over the length (flow path) of the wetlands 3-4 (HSFCW 3-4)*

Nitrite concentrations had shown a similar behaviour. They had risen until a flow path of 0.25 cm to fall afterwards to a stable level. Most nitrate appeared in the first 25 cm; here had been around 10.75 mg/L ammonium eliminated by the systems and 3.74 mg/L nitrate remained in the porewater. If the water loss in the small area of only 25 cm could been assumed as comparable - around 65.2 % of the ammonium had been oxidized to nitrate.

The physical parameters Eh and pH in figure 21 had shown no irregularities and had been very similar to those of the wetlands 1 and 2. At least the loss of nitrate concentration around the 40th cm had indicated reductive activity inside microgradients.

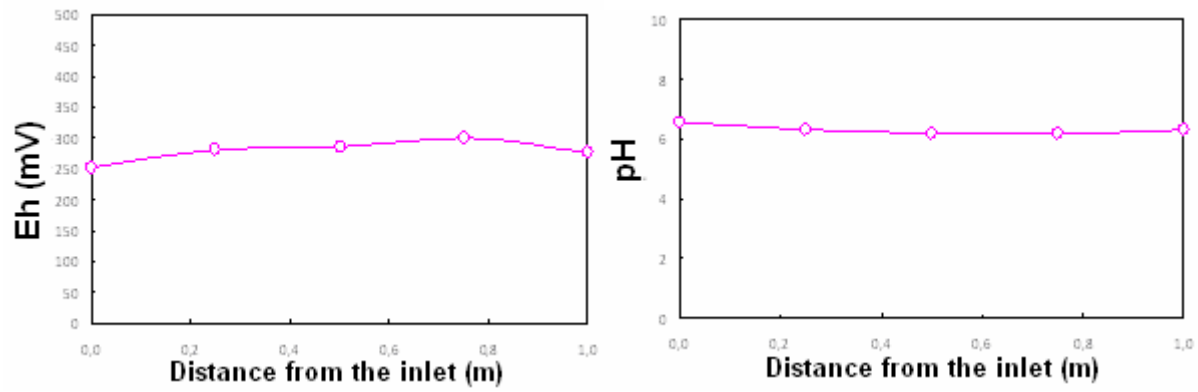

figure 21: *Mean Eh and pH over the length for the first group of wetlands 3-4 (HSFCW 3-4)*

4 Conclusions

Nitrogen removal is often seen as a minor advantage of constructed wetlands. For no other contaminant elimination process so many diverse factors are of relevance. Plant uptake of nitrogen has only a limited importance for the overall elimination according Kadlec and Knight (1996) [8]. Main nitrogen removal is usually realised via nitrification (oxidative) and denitrification (reductive) processes; they influence each other dynamically.

Two groups of systems containing each two wetlands and one reactor (PFR) had been run to characterise the differences between the removal activities when they were run with different compositions of waste waters with different nitrogen loads and species.

To get a picture of the nitrogen transformation inside the systems ammonium-nitrogen, nitrite-nitrogen and nitrate-nitrogen had been measured. Eh and pH had been measured to explain and analyse irregularities and changes. The observation of phosphate had been necessary to prevent limitation or over-fertilization and sign irregularities in processes of the model wetlands. Water loss had been measured to be able to calculate loads.

A limitation of any factor could not have been observed at any time. Even if horizontal flow wetlands often favour reductive processes and are oxygen limited, these effect could not been detected for any group or system. The dimensions of the systems could have been to small to prevent enough oxygen to pass all depths to the ground even if the biota had been not inhibited and had seemed to use the oxygen optimal (indicated by the high ammonium oxidation).

The systems adapted all well to the rise of the inflow rate and reached after some time again similar or almost the same removal rates.

To sum up, the systems had been better able to handle smaller ammonium amounts with some nitrate than a same stoichiometrical amount of nitrogen in

form of ammonium only. When the wetlands and reactors of every group had been considered together, the systems run with ammonium and nitrate had shown a 4.85 % higher decomposition rate. The differences had been most distinct at the reactors.

Nitrite as intermediate product of the nitrification had been in its concentration always low, the two steps of the nitrification seemed to be interlocked perfectly. Also assumed reductive processes did not let the nitrite concentrations rose to a risky concentration. So, there had been never a risk of a nitrite toxication. The reductive milieu in the reactors reacted with much higher nitrite values to the inflow rise. Here the reactor feed with ammonium and nitrate surpassed the values of the one feed with ammonium only. The PFR feed with ammonium and nitrate reacted to the rise with the loss of its dominant reductive milieu. This could have been a sign for the higher sensitivity of the reducing biota/ processes.

The nitrate removal of the wetlands 1 and 2 had been over 90 % together with the high removal for ammonium these systems removed the nitrogen almost completely. The wetlands 3 and 4 had accumulated nitrate through nitrification, the outflow values had been comparable to those of the wetlands 1 and 2. It could be assumed that the nitrogen loads for similar systems could be also similar (for a nitrogen feed that is not limiting or dangerous for the growth of the nitrogen using bacteria). The wetlands had reached innocuous nitrogen outflow concentrations never mind if their inflow consisted of ammonium or ammonium and nitrate.

The wetlands had been more effective in the nitrogen removal than the reactors. The important transformation processes already had happened in the first cm of the systems. In the following flow path concentrations had been stable, a dynamical regulation of reductive and oxidizing processes could have been assumed. The pH-values also confirmed this suggestion. They had been stable and neutral and never inclined to acid or alkaline milieu like it would have been with strong dominant reductive or oxidizing processes. Reductive conditions

could not been detected through Eh measurement; oxygen seemed to be present also in the deep layers. Reductive processes seemed to take place in small isolated zones of micro niches and biofilms or flocks.

New research should contain pulse loading experiments to broaden the gained knowledge about the nitrogen transformation processes in constructed wetlands. Also the use of another nitrogen source for the bacteria for example a waste water just containing nitrate could provide interesting data. The systems had been able to decrease the nitrogen loads in the first cm of the flow path and in the outflow almost complete removal was reached; probable they could be able to bear even higher loads.

Addendum

I Value Tables

I.I Ammonium-Nitrogen Values HSFCW

Date	Days	Lab-scale HSFCWs 1 Distance from the Inlet (m)					Inflow Rate	Outflow Rate	Inflow Load	Outflow Load
		0	0,25	0,5	0,75	1	L/d	L/d	mg/d	mg/d
23.03.2010	12	10,00	3,85	3,20	4,28	5,20	3,0	0,0	30,39	0,00
30.03.2010	19	10,00	1,13	0,43	0,16	0,00	3,1	0,0	30,66	0,00
06.04.2010	26	10,00	0,16	0,00	0,00	0,00	3,1	0,0	30,69	0,00
14.04.2010	34	10,00	0,00	0,00	0,00	0,00	3,0	0,0	30,49	0,00
21.04.2010	41	10,00	0,04	0,00	0,00	0,00	3,1	0,1	30,75	0,00
27.04.2010	47	10,00	0,00	0,00	0,00	0,00	3,1	0,0	31,36	0,00
05.05.2010	55	10,00	0,27	0,12	0,00	0,00	4,2	1,5	41,88	0,00
10.05.2010	60	10,00	0,04	0,00	0,00	0,00	3,9	1,2	39,14	0,00
18.05.2010	68	10,00	0,00	0,00	0,00	0,00	3,9	1,3	38,54	0,00
27.05.2010	77	10,00	0,00	0,00	0,00	0,00	4,1	1,5	41,06	0,00
01.06.2010	82	10,00	0,00	0,00	0,00	0,00	4,13	1,48	41,32	0,00
09.06.2010	90	10,00	0,00	0,00	0,00	0,00	4,12	1,36	41,16	0,00

Date	Days	Lab-scale HSFCWs 2 Distance from the Inlet (m)					Inflow Rate	Outflow Rate	Inflow Load	Outflow Load
		0	0,25	0,5	0,75	1	L/d	L/d	mg/d	mg/d
23.03.2010	12	10,00	0,00	0,00	0,00	0,00	3,0	0,0	29,88	0,00
30.03.2010	19	10,00	0,97	0,74	0,50	0,00	3,1	0,7	31,39	0,00
06.04.2010	26	10,00	0,82	0,00	0,00	0,00	3,1	0,2	31,28	0,00
14.04.2010	34	10,00	0,00	0,00	0,00	0,00	3,1	0,7	31,07	0,00
21.04.2010	41	10,00	0,00	0,00	0,00	0,08	3,1	0,5	31,32	0,04
27.04.2010	47	10,00	0,04	0,00	0,00	0,00	3,1	0,0	31,44	0,00
05.05.2010	55	10,00	2,72	0,00	0,00	0,00	4,3	2,1	42,65	0,00
10.05.2010	60	10,00	0,47	0,51	0,23	0,00	4,1	1,9	41,02	0,00
18.05.2010	68	10,00	0,00	0,00	0,00	0,00	4,2	1,9	42,26	0,00
27.05.2010	77	10,00	0,00	0,00	0,00	0,00	4,5	2,0	44,87	0,00
01.06.2010	82	10,00	0,00	0,00	0,00	0,00	4,43	2,18	44,26	0,00
09.06.2010	90	10,00	0,00	0,00	0,00	0,00	4,17	1,95	41,73	0,00

Date	Days	Lab-scale HSFCWs 3 Distance from the Inlet (m)					Inflow Rate	Outflow Rate	Inflow Load	Outflow Load
		0	0,25	0,5	0,75	1	L/d	L/d	mg/d	mg/d
23.03.2010	12									
30.03.2010	19	25,00	11,85	7,45	2,64	0,00	2,8	0,2	70,34	0,00
06.04.2010	26	25,00	10,03	4,98	0,62	0,70	2,9	1,1	71,60	0,77
14.04.2010	34	25,00	14,89	4,86	0,16	0,00	2,8	0,9	69,76	0,00
21.04.2010	41	25,00	20,34	8,71	0,16	0,11	2,8	0,7	70,14	0,08

Date	Days	Lab-scale HSFCWs 3 Distance from the Inlet (m)					Inflow Rate	Outflow Rate	Inflow Load	Outflow Load
		0	0,25	0,5	0,75	1	L/d	L/d	mg/d	mg/d
27.04.2010	47	25,00	17,23	7,27	0,47	0,00	2,8	0,6	70,32	0,00
05.05.2010	55	25,00	8,01	5,25	1,48	0,90	4,7	1,9	118,18	1,68
10.05.2010	60	25,00	4,04	2,06	1,01	0,90	4,6	2,2	114,94	1,99
18.05.2010	68	25,00	21,74	9,68	0,23	0,00	4,2	1,8	103,85	0,00
27.05.2010	77	25,00	15,24	14,04	6,38	0,00	4,2	1,5	105,75	0,00
01.06.2010	82	25,00	12,76	10,38	6,07	2,80	4,42	1,61	110,39	4,51
09.06.2010	90	25,00	21,16	7,78	3,11	1,01	3,65	0,35	91,33	0,35

Date	Days	Lab-scale HSFCWs 4 Distance from the Inlet (m)					Inflow Rate	Outflow Rate	Inflow Load	Outflow Load
		0	0,25	0,5	0,75	1	L/d	L/d	mg/d	mg/d
23.03.2010	12	25,00	17,60	13,40	2,26	0,00	2,9	0,8	72,41	0,00
30.03.2010	19	25,00	10,77	5,60	0,16	0,10	2,8	0,2	70,60	0,02
06.04.2010	26	25,00	16,99	4,12	0,54	0,00	2,9	0,6	72,98	0,00
14.04.2010	34	25,00	8,71	3,23	0,00	0,00	2,9	0,5	71,26	0,00
21.04.2010	41	25,00	25,00	7,70	0,54	0,31	2,9	0,6	71,64	0,17
27.04.2010	47	25,00	13,61	6,14	0,00	0,31	2,9	0,4	72,43	0,11
05.05.2010	55	25,00	11,78	6,42	1,71	0,00	3,4	1,4	85,25	0,00
10.05.2010	60	25,00	15,87	9,41	1,63	1,63	4,3	1,6	106,88	2,69
18.05.2010	68	25,00	14,86	6,14	0,93	0,00	4,1	1,6	102,95	0,00
27.05.2010	77	25,00	13,73	12,30	0,00	0,00	4,1	1,6	102,52	0,00
01.06.2010	82	25,00	7,58	1,36	0,00	0,00	4,06	1,29	101,51	0,00
09.06.2010	90	25,00	14,00	10,89	2,02	0,62	4,27	1,28	106,69	0,80

I.II Nitrite-Nitrogen Values HSFCW

Date	Days	Lab-scale HSFCWs 1 Distance from the Inlet (m)					Inflow Rate	Outflow Rate	Inflow Load	Outflow Load
		0	0,25	0,5	0,75	1	L/d	L/d	mg/d	mg/d
23.03.2010	12	0,000	0,032	0,027	0,037	0,037	3,039	0,000	0,000	0,000
30.03.2010	19	0,000	0,015	0,011	0,012	0,016	3,066	0,000	0,000	0,000
06.04.2010	26	0,000	0,020	0,014	0,016	0,015	3,069	0,000	0,000	0,000
14.04.2010	34	0,000	0,021	0,023	0,023	0,000	3,049	0,000	0,000	0,000
21.04.2010	41	0,000	0,019	0,018	0,020	0,000	3,075	0,125	0,000	0,000
27.04.2010	47	0,000	0,012	0,014	0,019	0,000	3,136	0,033	0,000	0,000
05.05.2010	55	0,000	0,007	0,010	0,015	0,000	4,188	1,514	0,000	0,000
10.05.2010	60	0,000	0,006	0,053	0,027	0,000	3,914	1,249	0,000	0,000
18.05.2010	68	0,000	0,004	0,003	0,006	0,012	3,854	1,274	0,000	0,015
27.05.2010	77	0,000	0,004	0,005	0,007	0,009	4,106	1,511	0,000	0,013
01.06.2010	82	0,000	0,003	0,005	0,006	0,009	4,132	1,476	0,000	0,013
09.06.2010	90	0,000	0,044	0,009	0,010	0,018	4,116	1,365	0,000	0,025

Date	Days	Lab-scale HSFCWs 2 Distance from the Inlet (m)					Inflow Rate	Outflow Rate	Inflow Load	Outflow Load
		0	0,25	0,5	0,75	1	L/d	L/d	mg/d	mg/d
23.03.2010	12	0,000	0,038	0,037	0,025	0,047	2,988	0,038	0,000	0,002
30.03.2010	19	0,000	0,011	0,011	0,013	0,064	3,139	0,718	0,000	0,046
06.04.2010	26	0,000	0,008	0,011	0,012	0,021	3,128	0,177	0,000	0,004
14.04.2010	34	0,000	0,016	0,015	0,018	0,000	3,107	0,656	0,000	0,000
21.04.2010	41	0,000	0,016	0,015	0,023	0,000	3,132	0,521	0,000	0,000
27.04.2010	47	0,000	0,013	0,016	0,012	0,000	3,144	0,000	0,000	0,000
05.05.2010	55	0,000	0,023	0,006	0,004	0,000	4,265	2,056	0,000	0,000
10.05.2010	60	0,000	0,012	0,003	0,003	0,000	4,102	1,858	0,000	0,000
18.05.2010	68	0,000	0,003	0,002	0,006	0,016	4,226	1,939	0,000	0,031
27.05.2010	77	0,000	0,038	0,023	0,004	0,014	4,487	2,036	0,000	0,028
01.06.2010	82	0,000	0,004	0,004	0,033	0,015	4,426	2,182	0,000	0,033
09.06.2010	90	0,000	0,007	0,005	0,005	0,010	4,173	1,954	0,000	0,020

Date	Days	Lab-scale HSFCWs 3 Distance from the Inlet (m)					Inflow Rate	Outflow Rate	Inflow Load	Outflow Load
		0	0,25	0,5	0,75	1	L/d	L/d	mg/d	mg/d
23.03.2010	12									
30.03.2010	19	0,000	0,023	0,028	0,028	0,027	2,814	0,158	0,000	0,004
06.04.2010	26	0,000	0,016	0,013	0,013	0,010	2,864	1,107	0,000	0,011
14.04.2010	34	0,000	0,016	0,016	0,010	0,000	2,790	0,920	0,000	0,000
21.04.2010	41	0,000	0,007	0,006	0,006	0,000	2,806	0,746	0,000	0,000
27.04.2010	47	0,000	0,007	0,006	0,005	0,000	2,813	0,648	0,000	0,000
05.05.2010	55	0,000	0,026	0,026	0,012	0,000	4,727	1,870	0,000	0,000
10.05.2010	60	0,000	0,015	0,013	0,009	0,000	4,597	2,209	0,000	0,000
18.05.2010	68	0,000	0,041	0,034	0,028	0,038	4,154	1,793	0,000	0,069
27.05.2010	77	0,000	0,044	0,043	0,015	0,017	4,230	1,506	0,000	0,026
01.06.2010	82	0,000	0,040	0,037	0,015	0,012	4,416	1,610	0,000	0,020
09.06.2010	90	0,000	0,012	0,011	0,005	0,005	3,653	0,347	0,000	0,002

Date	Days	Lab-scale HSFCWs 4 Distance from the Inlet (m)					Inflow Rate	Outflow Rate	Inflow Load	Outflow Load
		0	0,25	0,5	0,75	1	L/d	L/d	mg/d	mg/d
23.03.2010	12	0,000	0,029	0,034	0,032	0,033	2,896	0,791	0,000	0,026
30.03.2010	19	0,000	0,008	0,008	0,012	0,025	2,824	0,156	0,000	0,004
06.04.2010	26	0,000	0,028	0,036	0,016	0,016	2,919	0,592	0,000	0,010
14.04.2010	34	0,000	0,016	0,016	0,012	0,000	2,851	0,506	0,000	0,000
21.04.2010	41	0,000	0,008	0,009	0,005	0,000	2,865	0,558	0,000	0,000
27.04.2010	47	0,000	0,006	0,009	0,012	0,000	2,897	0,350	0,000	0,000
05.05.2010	55	0,000	0,023	0,017	0,025	0,000	3,410	1,394	0,000	0,000
10.05.2010	60	0,000	0,007	0,007	0,011	0,016	4,275	1,649	0,000	0,027
18.05.2010	68	0,000	0,027	0,039	0,054	0,032	4,118	1,597	0,000	0,052
27.05.2010	77	0,000	0,052	0,059	0,040	0,061	4,101	1,586	0,000	0,097
01.06.2010	82	0,000	0,038	0,051	0,037	0,073	4,060	1,291	0,000	0,094

Date	Days	Lab-scale HSFCWs 4 Distance from the Inlet (m)					Inflow Rate	Outflow Rate	Inflow Load	Outflow Load
		0	0,25	0,5	0,75	1	L/d	L/d	mg/d	mg/d
09.06.2010	90	0,000	0,011	0,009	0,014	0,015	4,268	1,284	0,000	0,019

I.III Nitrate-Nitrogen Values HSFCW

Date	Days	Lab-scale HSFCWs 1 Distance from the Inlet (m)					Inflow Rate	Outflow Rate	Inflow Load	Outflow Load
		0	0,25	0,5	0,75	1	L/d	L/d	mg/d	mg/d
23.03.2010	12	15,00	1,34	1,64	1,81	1,81	3,04	0,00	45,59	0,00
30.03.2010	19	15,00	1,20	1,04	1,38	0,99	3,07	0,00	45,99	0,00
06.04.2010	26	15,00	0,68	0,32	0,00	0,34	3,07	0,00	46,04	0,00
14.04.2010	34	15,00	1,47	1,55	1,42	0,84	3,05	0,00	45,74	0,00
21.04.2010	41	15,00	0,99	0,87	1,33	0,63	3,08	0,13	46,13	0,08
27.04.2010	47	15,00	1,37	1,69	1,22	0,90	3,14	0,03	47,04	0,03
05.05.2010	55	15,00	0,76	0,77	0,29	0,50	4,19	1,51	62,82	0,75
10.05.2010	60	15,00	4,98	4,02	4,99	4,90	3,91	1,25	58,71	6,12
18.05.2010	68	15,00	1,55	1,83	0,61	1,81	3,85	1,27	57,81	2,30
27.05.2010	77	15,00	5,40	5,18	4,74	4,54	4,11	1,51	61,60	6,86
01.06.2010	82	15,00	4,97	4,82	4,22	4,70	4,13	1,48	61,98	6,93
09.06.2010	90	15,00	1,17	0,95	0,38	3,70	4,12	1,36	61,73	5,05

Date	Days	Lab-scale HSFCWs 2 Distance from the Inlet (m)					Inflow Rate	Outflow Rate	Inflow Load	Outflow Load
		0	0,25	0,5	0,75	1	L/d	L/d	mg/d	mg/d
23.03.2010	12	15,00	1,15	1,11	0,81	0,00	2,99	0,04	44,82	0,00
30.03.2010	19	15,00	0,52	0,85	0,34	0,72	3,14	0,72	47,08	0,52
06.04.2010	26	15,00	2,66	0,51	0,59	0,81	3,13	0,18	46,91	0,14
14.04.2010	34	15,00	1,81	1,64	0,27	1,15	3,11	0,66	46,61	0,76
21.04.2010	41	15,00	0,81	0,87	1,08	1,35	3,13	0,52	46,98	0,71
27.04.2010	47	15,00	1,12	1,26	0,05	1,69	3,14	0,00	47,17	0,00
05.05.2010	55	15,00	0,84	0,59	0,00	1,13	4,27	2,06	63,98	2,32
10.05.2010	60	15,00	2,68	2,39	2,62	2,75	4,10	1,86	61,54	5,12
18.05.2010	68	15,00	2,00	4,02	10,86	12,74	4,23	1,94	63,39	24,69
27.05.2010	77	15,00	3,82	3,87	5,71	4,67	4,49	2,04	67,30	9,52
01.06.2010	82	15,00	3,56	3,75	4,67	3,84	4,43	2,18	66,39	8,38
09.06.2010	90	15,00	1,02	1,17	0,65	2,66	4,17	1,95	62,59	5,21

Date	Days	Lab-scale HSFCWs 3 Distance from the Inlet (m)					Inflow Rate	Outflow Rate	Inflow Load	Outflow Load
		0	0,25	0,5	0,75	1	L/d	L/d	mg/d	mg/d
23.03.2010	12									
30.03.2010	19	0,00	1,77	1,22	0,93	0,86	2,81	0,16	0,00	0,14
06.04.2010	26	0,00	3,56	1,55	4,11	0,65	2,86	1,11	0,00	0,72
14.04.2010	34	0,00	0,62	0,41	0,29	0,61	2,79	0,92	0,00	0,56

Date	Days	Lab-scale HSFCWs 3 Distance from the Inlet (m)					Inflow Rate	Outflow Rate	Inflow Load	Outflow Load
		0	0,25	0,5	0,75	1	L/d	L/d	mg/d	mg/d
21.04.2010	41	0,00	0,49	1,81	0,63	4,02	2,81	0,75	0,00	3,00
27.04.2010	47	0,00	0,40	0,35	0,54	0,70	2,81	0,65	0,00	0,45
05.05.2010	55	0,00	2,60	2,13	2,73	1,42	4,73	1,87	0,00	2,66
10.05.2010	60	0,00	3,93	4,63	4,38	6,59	4,60	2,21	0,00	14,56
18.05.2010	68	0,00	1,68	2,34	1,35	1,51	4,15	1,79	0,00	2,71
27.05.2010	77	0,00	6,12	7,17	5,28	4,13	4,23	1,51	0,00	6,22
01.06.2010	82	0,00	5,17	6,66	3,84	4,49	4,42	1,61	0,00	7,24
09.06.2010	90	0,00	1,72	0,54	0,99	1,74	3,65	0,35	0,00	0,60

Date	Days	Lab-scale HSFCWs 4 Distance from the Inlet (m)					Inflow Rate	Inflow Rate	Inflow Rate	Outflow Rate
		0	0,25	0,5	0,75	1	L/d	L/d	mg/d	mg/d
23.03.2010	12	0,00	1,54	1,46	1,87	2,03	2,90	0,79	0,00	1,61
30.03.2010	19	0,00	0,73	1,15	1,40	0,93	2,82	0,16	0,00	0,14
06.04.2010	26	0,00	3,48	4,91	4,76	1,11	2,92	0,59	0,00	0,65
14.04.2010	34	0,00	0,64	2,05	3,61	0,47	2,85	0,51	0,00	0,24
21.04.2010	41	0,00	0,49	0,45	0,29	0,68	2,87	0,56	0,00	0,38
27.04.2010	47	0,00	0,93	0,77	2,24	0,63	2,90	0,35	0,00	0,22
05.05.2010	55	0,00	3,09	3,00	3,50	3,50	3,41	1,39	0,00	4,88
10.05.2010	60	0,00	5,08	4,36	3,09	4,38	4,28	1,65	0,00	7,22
18.05.2010	68	0,00	2,51	2,69	3,21	1,99	4,12	1,60	0,00	3,17
27.05.2010	77	0,00	4,17	4,19	3,18	4,45	4,10	1,59	0,00	7,06
01.06.2010	82	0,00	2,45	2,70	2,78	4,27	4,06	1,29	0,00	5,51
09.06.2010	90	0,00	6,86	5,80	5,31	5,74	4,27	1,28	0,00	7,37

I.IV Redoxpotential HSFCW

Date	Days	Lab-scale HSFCWs 1 Distance from the Inlet (m)					Lab-scale HSFCWs 2 Distance from the Inlet (m)				
		0	0,25	0,5	0,75	1	0	0,25	0,5	0,75	1
23.03.2010	12	172	180,5	209	230	279	182,2	136,4	133,85	196	305,1
30.03.2010	19	117,3	117,35	118,3	118,8	139,9	201,4	218	229,5	285,4	266
06.04.2010	26	179	240,65	280	186,6	373	141	109,5	110,5	112	88
14.04.2010	34	125,9	150,95	150,8	150,5	150,2	185	168,5	174	197	308
21.04.2010	41	113	124,95	124,35	134,6	133,8	116	174,5	172,5	186	313
27.04.2010	47	254	202	186	140	254	116	220	193,5	186	334
05.05.2010	55	277	338,5	328	299	323	328	356	348	338	315
10.05.2010	60	271	280,5	257,5	233	207	314	372	379	376	230,6
18.05.2010	68	294	336	327	277	280	89	93,5	94	95	95
27.05.2010	77	320	322	299,5	282	293	320,8	366,4	370,25	375,2	397,4
01.06.2010	82	341	420	393	380	372	320,5	384,5	373,7	402	413
09.06.2010	90	315	362	335	303	335	415	395	373	355	339

Date	Days	Lab-scale HSFCWs 3 Distance from the Inlet (m)					Lab-scale HSFCWs 4 Distance from the Inlet (m)				
		0	0,25	0,5	0,75	1	0	0,25	0,5	0,75	1
23.03.2010	12						185,7	178,3	187,77	151,2	157,7
30.03.2010	19	201	204,5	191	187	203	206,7	163,95	163,95	193,4	163,8
06.04.2010	26	111	113,6	113,3	113	111,8	174	191	167,5	195	150
14.04.2010	34	112,8	117	116,7	116,6	122,3	170	207	178	189	173
21.04.2010	41	128,5	116,4	116,2	121,9	121,8	213	183	189,5	205	181
27.04.2010	47	227	255	283	282	258	155	199,5	202,5	227	204
05.05.2010	55	263	295,5	312	322	275	182	250,5	289	359	304
10.05.2010	60	308	324	318,5	311	283	349	258	234	259	294
18.05.2010	68	353	404	428	454	485	91	100	100	101	101
27.05.2010	77	254	362,5	364	347	350	305,1	344,45	344,25	367	358
01.06.2010	82	348	453	467	472	476	329	386,4	414	421	431
09.06.2010	90	293	323	357	408	436	337	364	378	414	408

I.V pH-Values HSFCW

Date	Days	Lab-scale HSFCWs 1 Distance from the Inlet (m)					Lab-scale HSFCWs 2 Distance from the Inlet (m)				
		0	0,25	0,5	0,75	1	0	0,25	0,5	0,75	1
23.03.2010	12	6,42	6,405	6,425	6,58	6,38	6,41	6,405	6,355	6,35	6,26
30.03.2010	19	6,43	6,405	6,455	6,4	6,47	6,4	6,41	6,415	6,4	6,29
06.04.2010	26	6,85	6,7	6,74	6,72	6,68	6,65	6,595	6,545	6,58	6,45
14.04.2010	34	6,78	6,73	6,745	6,77	6,85	6,77	6,59	6,58	6,56	6,65
21.04.2010	41	7,01	6,83	6,835	6,83	6,83	6,78	6,67	6,65	6,62	6,7
27.04.2010	47	6,88	6,705	6,735	6,71	6,75	6,67	6,515	6,605	6,62	6,73
05.05.2010	55	6,73	6,615	6,675	6,42	6,5	6,28	6,295	6,41	6,25	6,35
10.05.2010	60	6,14	6,29	6,485	6,38	6,62	6,35	6,24	6,28	6,28	6,45
18.05.2010	68	6,35	6,05	6,375	6,41	6,45	6,74	6,15	6,24	6,31	6,42
27.05.2010	77	7,6	7,1	7,18	7,35	6,84	6,08	6,01	6,185	6,31	6,4
01.06.2010	82	8,81	6,52	6,715	6,75	6,8	6,71	6,005	6,08	6,3	6,42
09.06.2010	90	7,67	7,57	7,73	7,85	7,45	6,48	6,26	6,39	6,29	6,26

Date	Days	Lab-scale HSFCWs 3 Distance from the Inlet (m)					Lab-scale HSFCWs 4 Distance from the Inlet (m)				
		0	0,25	0,5	0,75	1	0	0,25	0,5	0,75	1
23.03.2010	12						6,38	6,16	6,085	6,16	6,25
30.03.2010	19	6,09	6,165	6,185	6,19	6,38	6,2	6,215	6,15	6,06	6,27
06.04.2010	26	6,47	6,405	6,385	6,44	6,55	6,56	6,29	6,285	6,31	6,38
14.04.2010	34	6,51	6,4	6,38	6,42	6,77	6,73	6,395	6,36	6,42	6,77
21.04.2010	41	6,6	6,48	6,45	6,52	6,6	6,81	6,39	6,355	6,6	6,57
27.04.2010	47	6,56	6,4	6,335	6,35	6,38	6,6	6,405	6,3	6,35	6,48
05.05.2010	55	6,18	6,075	6,075	6,15	6,2	6,47	6,15	6,07	6,71	6,22
10.05.2010	60	6,39	6,065	6,045	6,14	6,07	6,22	5,94	5,995	6	6,17
18.05.2010	68	6,32	5,995	5,845	6,32	6,04	6,18	5,735	5,495	5,57	6,22
27.05.2010	77	7,28	7,355	7	7,12	7,16	6,15	5,93	5,55	5,37	5,8

Date	Days	Lab-scale HSFCWs 3 Distance from the Inlet (m)					Lab-scale HSFCWs 4 Distance from the Inlet (m)				
		0	0,25	0,5	0,75	1	0	0,25	0,5	0,75	1
01.06.2010	82	8,62	7,835	7,525	7,44	7,19	6,09	5,46	4,825	4,52	5,8
09.06.2010	90	7,37	7,01	6,49	5,7	5,31	5,74	5,49	5,26	4,47	5,64

I.VI Ammonium-Nitrogen Values Reactors

Date	Days	R3								
		Inflow	Outflow		Inflow Rate		Out-flow Rate	Water loss	Inflow Load	Outflow Load
			Ob-served	Final						
	d	mg/L	mg/L	mg/L	ml/min	L/d	L/d	%	mg/d	mg/d
22.03.2010	12	7,00	6,00	4,67	2,02	2,91	2,58	11,3	20,36	12,04
25.03.2010	15	7,00	6,90	5,37	2,02	2,91	2,45	15,8	20,36	13,14
29.03.2010	19	7,00	4,50	3,50	2,02	2,91	2,57	11,5	20,36	9,01
01.04.2010	22	7,00	5,70	4,43	2,02	2,91	2,57	11,5	20,36	11,41
06.04.2010	27	7,00	6,60	5,13	2,02	2,91	2,57	11,5	20,36	13,21
09.04.2010	30	7,00	5,60	4,36	2,01	2,89	2,53	12,6	20,26	11,02
12.04.2010	33	7,00	5,60	4,36	2,02	2,91	2,71	6,9	20,36	11,80
15.04.2010	36	7,00	6,00	4,67	2,02	2,91	2,71	6,9	20,36	12,64
19.04.2010	40	7,00	7,50	5,83	2,00	2,88	2,66	7,7	20,16	15,51
22.04.2010	43	7,00	8,30	6,46	2,00	2,88	2,66	7,7	20,16	17,16
27.04.2010	48	7,00	9,00	7,00	2,03	2,92	2,72	7,1	20,46	19,01
02.05.2010	53	10,00	10,40	8,09	2,83	4,08	3,91	4,0	40,75	31,65
05.05.2010	56	10,00	10,50	8,17	2,83	4,08	3,91	4,0	40,75	31,95
09.05.2010	60	10,00	14,80	10,00	2,82	4,06	3,82	5,9	40,61	38,21
13.05.2010	64	10,00	13,40	10,42	2,82	4,06	3,82	5,9	40,61	39,83
16.05.2010	67	10,00	11,30	8,79	2,83	4,08	3,82	6,3	40,75	33,56
20.05.2010	71	10,00	11,30	8,79	2,83	4,08	3,82	6,3	40,75	33,56
22.05.2010	73	10,00	9,80	7,62	2,83	4,08	3,70	9,3	40,75	28,17
26.05.2010	77	10,00	11,20	8,71	2,83	4,08	3,70	9,3	40,75	32,20
29.05.2010	80	10,00	10,70	8,32	2,82	4,06	3,76	7,3	40,61	31,33
01.06.2010	83	10,00	7,50	5,83	2,82	4,06	3,76	7,3	40,61	21,96
04.06.2010	86	10,00	8,40	6,53	2,82	4,06	3,76	7,3	40,61	24,59
08.06.2010	90	10,00	6,80	5,29	2,84	4,09	3,59	12,30	40,90	18,97
11.06.2010	93	10,00	4,40	3,42	2,84	4,09	3,59	12,30	40,90	12,27

Date	Days	R4								
		Inflow	Outflow		Inflow Rate		Out-flow Rate	Water loss	Inflow Load	Outflow Load
			Ob-served	Final						
	d	mg/L	mg/L	mg/L	ml/min	L/d	L/d	%	mg/d	mg/d
22.03.2010	12	17,50	21,60	16,80	2,02	2,91	2,40	17,50	50,90	40,32
25.03.2010	15	17,50	16,60	12,91	2,01	2,89	2,37	18,10	50,65	30,61
29.03.2010	19	17,50	15,00	11,67	2,00	2,88	2,25	21,90	50,40	26,24

Date	Days	R4								
		Inflow	Outflow		Inflow Rate		Out-flow Rate	Water loss	Inflow Load	Outflow Load
			Ob-served	Final						
	d	mg/L	mg/L	mg/L	ml/min	L/d	L/d	%	mg/d	mg/d
01.04.2010	22	17,50	14,90	11,59	2,00	2,88	2,25	21,90	50,40	26,07
06.04.2010	27	17,50	19,70	15,32	2,00	2,88	2,25	21,90	50,40	34,46
09.04.2010	30	17,50	16,00	12,44	2,00	2,88	2,11	26,90	50,40	26,20
12.04.2010	33	17,50	17,80	13,84	2,00	2,88	2,39	17,10	50,40	33,05
15.04.2010	36	17,50	18,30	14,23	2,00	2,88	2,39	17,10	50,40	33,98
19.04.2010	40	17,50	20,00	15,56	2,00	2,88	2,13	25,90	50,40	33,20
22.04.2010	43	17,50	19,10	14,86	2,00	2,88	2,13	25,90	50,40	31,70
27.04.2010	48	17,50	21,40	16,64	2,00	2,88	2,16	25,10	50,40	35,90
02.05.2010	53	25,00	34,50	26,83	2,79	4,02	3,49	13,10	100,44	93,68
05.05.2010	56	25,00	17,50	13,61	2,79	4,02	3,49	13,10	100,44	47,52
09.05.2010	60	25,00	24,40	18,98	2,80	4,03	3,44	14,60	100,80	65,35
13.05.2010	64	25,00	31,30	24,34	2,80	4,03	3,44	14,60	100,80	83,83
16.05.2010	67	25,00	28,90	22,48	2,81	4,05	3,50	13,40	101,16	78,77
20.05.2010	71	25,00	37,60	29,24	2,79	4,02	3,47	13,60	100,44	100,40
22.05.2010	73	25,00	31,90	24,81	2,80	4,03	3,51	13,00	100,80	87,03
26.05.2010	77	25,00	33,10	25,74	2,80	4,03	3,51	13,00	100,80	90,31
29.05.2010	80	25,00	32,50	25,28	2,83	4,08	3,53	13,40	101,88	89,21
01.06.2010	83	25,00	29,40	22,87	2,83	4,08	3,53	13,40	101,88	80,70
04.06.2010	86	25,00	29,50	22,94	2,83	4,08	3,53	13,40	101,88	80,97
08.06.2010	90	25,00	30,20	23,49	2,81	4,05	3,53	12,80	101,16	82,88
11.06.2010	93	25,00	29,30	22,79	2,81	4,05	3,53	12,80	101,16	80,41

I.VII Nitrite-Nitrogen Values Reactors

Date	Days	R3								
		Inflow	Outflow		Inflow Rate		Outflow Rate	Water loss	Inflow Load	Outflow Load
			Observed	Final						
	d	mg/L	mg/L	mg/L	ml/min	L/d	L/d	%	mg/d	mg/d
22.03.2010	12	0,00	0,00	0,00	2,02	2,91	2,58	11,3	0,00	0,00
25.03.2010	15	0,00	0,13	0,04	2,02	2,91	2,45	15,8	0,00	0,10
29.03.2010	19	0,00	0,05	0,02	2,02	2,91	2,57	11,5	0,00	0,04
01.04.2010	22	0,00	0,08	0,02	2,02	2,91	2,57	11,5	0,00	0,06
06.04.2010	27	0,00	0,04	0,01	2,02	2,91	2,57	11,5	0,00	0,03
09.04.2010	30	0,00	0,06	0,02	2,01	2,89	2,53	12,6	0,00	0,05
12.04.2010	33	0,00	0,07	0,02	2,02	2,91	2,71	6,9	0,00	0,06
15.04.2010	36	0,00	0,02	0,01	2,02	2,91	2,71	6,9	0,00	0,02
19.04.2010	40	0,00	0,04	0,01	2,00	2,88	2,66	7,7	0,00	0,03
22.04.2010	43	0,00	0,04	0,01	2,00	2,88	2,66	7,7	0,00	0,03
27.04.2010	48	0,00	0,02	0,01	2,03	2,92	2,72	7,1	0,00	0,02
02.05.2010	53	0,00	0,21	0,06	2,83	4,08	3,91	4,0	0,00	0,25
05.05.2010	56	0,00	0,02	0,01	2,83	4,08	3,91	4,0	0,00	0,02

Date	Days	R3								
		Inflow	Outflow		Inflow Rate		Outflow Rate	Water loss	Inflow Load	Outflow Load
			Observed	Final						
	d	mg/L	mg/L	mg/L	ml/min	L/d	L/d	%	mg/d	mg/d
09.05.2010	60	0,00	0,05	0,02	2,82	4,06	3,82	5,9	0,00	0,06
13.05.2010	64	0,00	0,04	0,01	2,82	4,06	3,82	5,9	0,00	0,05
16.05.2010	67	0,00	0,23	0,07	2,83	4,08	3,82	6,3	0,00	0,27
20.05.2010	71	0,00	0,05	0,02	2,83	4,08	3,82	6,3	0,00	0,06
22.05.2010	73	0,00	0,18	0,05	2,83	4,08	3,70	9,3	0,00	0,20
26.05.2010	77	0,00	0,50	0,15	2,83	4,08	3,70	9,3	0,00	0,56
29.05.2010	80	0,00	1,400	0,110	2,82	4,06	3,76	7,3	0,00	0,41
01.06.2010	83	0,00	1,270	0,120	2,82	4,06	3,76	7,3	0,00	0,45
04.06.2010	86	0,00	0,107	0,033	2,82	4,06	3,76	7,3	0,00	0,12
08.06.2010	90	0,00	0,019	0,006	2,84	4,09	3,59	12,3	0,00	0,02
11.06.2010	93	0,00	0,052	0,016	2,84	4,09	3,59	12,30	0,00	0,06

Date	Days	R4								
		Inflow	Outflow		Inflow Rate		Out-flow Rate	Water loss	Inflow Load	Outflow Load
			Ob-served	Final						
	d	mg/L	mg/L	mg/L	ml/min	L/d	L/d	%	mg/d	mg/d
22.03.2010	12	0,0	0,00	0,00	2,02	2,91	2,40	17,50	0,00	0,00
25.03.2010	15	0,0	0,06	0,02	2,01	2,89	2,37	18,10	0,00	0,04
29.03.2010	19	0,0	0,04	0,01	2,00	2,88	2,25	21,90	0,00	0,03
01.04.2010	22	0,0	0,05	0,02	2,00	2,88	2,25	21,90	0,00	0,03
06.04.2010	27	0,0	0,02	0,00	2,00	2,88	2,25	21,90	0,00	0,01
09.04.2010	30	0,0	0,05	0,02	2,00	2,88	2,11	26,90	0,00	0,03
12.04.2010	33	0,0	0,05	0,02	2,00	2,88	2,39	17,10	0,00	0,04
15.04.2010	36	0,0	0,03	0,01	2,00	2,88	2,39	17,10	0,00	0,02
19.04.2010	40	0,0	0,03	0,01	2,00	2,88	2,13	25,90	0,00	0,02
22.04.2010	43	0,0	0,02	0,01	2,00	2,88	2,13	25,90	0,00	0,01
27.04.2010	48	0,0	0,01	0,00	2,00	2,88	2,16	25,10	0,00	0,01
02.05.2010	53	0,0	0,02	0,01	2,79	4,02	3,49	13,10	0,00	0,02
05.05.2010	56	0,0	0,00	0,00	2,79	4,02	3,49	13,10	0,00	0,00
09.05.2010	60	0,0	0,03	0,01	2,80	4,03	3,44	14,60	0,00	0,03
13.05.2010	64	0,0	0,01	0,00	2,80	4,03	3,44	14,60	0,00	0,01
16.05.2010	67	0,0	0,03	0,01	2,81	4,05	3,50	13,40	0,00	0,03
20.05.2010	71	0,0	0,05	0,02	2,79	4,02	3,47	13,60	0,00	0,05
22.05.2010	73	0,0	0,04	0,01	2,80	4,03	3,51	13,00	0,00	0,04
26.05.2010	77	0,0	0,02	0,01	2,80	4,03	3,51	13,00	0,00	0,02
29.05.2010	80	0,0	0,120	0,037	2,83	4,08	3,53	13,40	0,00	0,13
01.06.2010	83	0,0	0,140	0,043	2,83	4,08	3,53	13,40	0,00	0,15
04.06.2010	86	0,0	0,017	0,005	2,83	4,08	3,53	13,40	0,00	0,02
08.06.2010	90	0,0	0,012	0,004	2,81	4,05	3,53	12,80	0,00	0,01
11.06.2010	93	0,0	0,027	0,008	2,81	4,05	3,53	12,80	0,00	0,03

I.VIII Nitrate-Nitrogen Values Reactors

Date	Days	R3								
		Inflow	Outflow		Inflow Rate		Outflow Rate	Water loss	Inflow Load	Outflow Load
			Observed	Final						
	d	mg/L	mg/L	mg/L	ml/min	L/d	L/d	%	mg/d	mg/d
22.03.2010	12	10,50	0,00	0,00	2,02	2,91	2,58	11,3	30,54	0,00
25.03.2010	15	10,50	3,80	0,86	2,02	2,91	2,45	15,8	30,54	2,10
29.03.2010	19	10,50	1,10	0,25	2,02	2,91	2,57	11,5	30,54	0,64
01.04.2010	22	10,50	3,80	0,86	2,02	2,91	2,57	11,5	30,54	2,21
06.04.2010	27	10,50	0,60	0,14	2,02	2,91	2,57	11,5	30,54	0,35
09.04.2010	30	10,50	2,00	0,45	2,01	2,89	2,53	12,6	30,39	1,14
12.04.2010	33	10,50	1,70	0,38	2,02	2,91	2,71	6,9	30,54	1,04
15.04.2010	36	10,50	1,10	0,25	2,02	2,91	2,71	6,9	30,54	0,67
19.04.2010	40	10,50	2,40	0,54	2,00	2,88	2,66	7,7	30,24	1,44
22.04.2010	43	10,50	1,40	0,32	2,00	2,88	2,66	7,7	30,24	0,84
27.04.2010	48	10,50	0,00	0,00	2,03	2,92	2,72	7,1	30,69	0,00
02.05.2010	53	15,00	0,00	0,00	2,83	4,08	3,91	4,0	61,13	0,00
05.05.2010	56	15,00	0,00	0,00	2,83	4,08	3,91	4,0	61,13	0,00
09.05.2010	60	15,00	0,90	0,20	2,82	4,06	3,82	5,9	60,91	0,78
13.05.2010	64	15,00	0,50	0,11	2,82	4,06	3,82	5,9	60,91	0,43
16.05.2010	67	15,00	1,40	0,32	2,83	4,08	3,82	6,3	61,13	1,21
20.05.2010	71	15,00	1,00	0,23	2,83	4,08	3,82	6,3	61,13	0,86
22.05.2010	73	15,00	15,00	3,39	2,83	4,08	3,70	9,3	61,13	12,52
26.05.2010	77	15,00	9,90	2,24	2,83	4,08	3,70	9,3	61,13	8,26
29.05.2010	80	15,00	17,20	3,88	2,82	4,06	3,76	7,3	60,91	14,62
01.06.2010	83	15,00	17,80	4,02	2,82	4,06	3,76	7,3	60,91	15,13
04.06.2010	86	15,00	15,20	3,43	2,82	4,06	3,76	7,3	60,91	12,92
08.06.2010	90	15,00	3,90	0,88	2,84	4,09	3,59	12,3	61,34	3,16
11.06.2010	93	15,00	4,30	0,97	2,84	4,09	3,59	12,3	61,34	3,48

Date	Days	R4								
		Inflow	Outflow		Inflow Rate		Out-flow Rate	Water loss	Inflow Load	Outflow Load
			Ob-served	Final						
	d	mg/L	mg/L	mg/L	ml/min	L/d	L/d	%	mg/d	mg/d
22.03.2010	12	0,0	0,00	0,00	2,02	2,91	2,40	17,50	0,00	0,00
25.03.2010	15	0,0	0,00	0,00	2,01	2,89	2,37	18,10	0,00	0,00
29.03.2010	19	0,0	0,00	0,00	2,00	2,88	2,25	21,90	0,00	0,00
01.04.2010	22	0,0	4,30	0,97	2,00	2,88	2,25	21,90	0,00	2,18
06.04.2010	27	0,0	0,50	0,11	2,00	2,88	2,25	21,90	0,00	0,25
09.04.2010	30	0,0	2,20	0,50	2,00	2,88	2,11	26,90	0,00	1,05
12.04.2010	33	0,0	2,50	0,56	2,00	2,88	2,39	17,10	0,00	1,35
15.04.2010	36	0,0	0,70	0,16	2,00	2,88	2,39	17,10	0,00	0,38
19.04.2010	40	0,0	0,70	0,16	2,00	2,88	2,13	25,90	0,00	0,34
22.04.2010	43	0,00	1,50	0,34	2,00	2,88	2,13	25,90	0,00	0,72

Date	Days	R4								
		Inflow	Outflow		Inflow Rate		Out-flow Rate	Water loss	Inflow Load	Outflow Load
			Ob-served	Final						
	d	mg/L	mg/L	mg/L	ml/min	L/d	L/d	%	mg/d	mg/d
27.04.2010	48	0,00	0,10	0,02	2,00	2,88	2,16	25,10	0,00	0,05
02.05.2010	53	0,00	0,40	0,09	2,79	4,02	3,49	13,10	0,00	0,32
05.05.2010	56	0,00	0,20	0,05	2,79	4,02	3,49	13,10	0,00	0,16
09.05.2010	60	0,00	1,70	0,38	2,80	4,03	3,44	14,60	0,00	1,32
13.05.2010	64	0,00	0,08	0,02	2,80	4,03	3,44	14,60	0,00	0,06
16.05.2010	67	0,00	2,80	0,63	2,81	4,05	3,50	13,40	0,00	2,22
20.05.2010	71	0,00	1,80	0,41	2,79	4,02	3,47	13,60	0,00	1,41
22.05.2010	73	0,00	4,60	1,04	2,80	4,03	3,51	13,00	0,00	3,64
26.05.2010	77	0,00	2,50	0,56	2,80	4,03	3,51	13,00	0,00	1,98
29.05.2010	80	0,00	15,30	3,45	2,83	4,08	3,53	13,40	0,00	12,19
01.06.2010	83	0,00	11,20	2,53	2,83	4,08	3,53	13,40	0,00	8,93
04.06.2010	86	0,00	14,80	3,34	2,83	4,08	3,53	13,40	0,00	11,79
08.06.2010	90	0,00	3,10	0,70	2,81	4,05	3,53	12,80	0,00	2,47
11.06.2010	93	0,00	4,40	0,99	2,81	4,05	3,53	12,80	0,00	3,51

I.IX Redoxpotential and ph-Values Reactors

Date	Days	R3			R4		
		pH	rH		pH	rH	
			mV			mV	
	d		Obs.	Final		Obs.	Final
22.03.2010	12	5,99	-471	-263	5,92	-392	-181
25.03.2010	15	6,01	-475	-267	5,90	-391	-180
29.03.2010	19	5,99	-476	-268	5,94	-387	-176
01.04.2010	22	5,99	-474	-266	5,94	-381	-170
06.04.2010	27	6,04	-475	-267	5,97	-382	-171
09.04.2010	30	5,93	-469	-261	5,87	-378	-167
12.04.2010	33	5,95	-473	-265	5,92	-390	-179
15.04.2010	36	5,99	-472	-264	5,89	-385	-174
19.04.2010	40	6	-468	-260	6,47	-417	-206
22.04.2010	43	6,05	-469	-261	5,34	-415	-204
27.04.2010	48	6,01	-472	-264	4,83	-383	-172
02.05.2010	53	6,02	-465	-257	6,71	-349	-138
05.05.2010	56	6	-462	-254	5,9	-344	-133
09.05.2010	60	6,06	-478	-270	5,83	-347	-136
13.05.2010	64	6,19	-468	-260	5,43	-356	-145
16.05.2010	67	6,14	-233	-25	5,83	-341	-130

Date	Days	R3			R4		
		pH	rH		pH	rH	
			mV			mV	
	d		Obs.	Final		Obs.	Final
20.05.2010	71	5,95	-450	-242	5,38	-344	-133
22.05.2010	73	6,06	-277	-69	5,78	-356	-145
26.05.2010	77	5,94	6	214	5,13	-365	-154
29.05.2010	80	6,08	68	276	5,79	-343	-132
01.06.2010	83	5,88	45	253	5,72	-355	-144
04.06.2010	86	5,87	56	264	5,8	-360	-149
08.06.2010	90	5,84	-454	-246	5,69	-365	-154
11.06.2010	93	5,92	-387	-179	5,82	-366	-155

II. Composition of the Artificial Wastewater Concentrates

Concentrate $I_{3,4}$ (500-fold-concentrated) (concentrate $I_{3,4}$)

sodium acetate, anhydrous	14,64	g/L
sodium benzoate	13,39	g/L
dipotassium phosphate x 3 H_2O	18,35	g/L
sodium chloride	3,50	g/L

Concentrate II_3 (500-fold-concentrated) (concentrate II_3)

(for R3 und WL1,2)

sodium nitrate	45,54	g/L
ammonium chloride	19,07	g/L
magnesium chloride	0,825	g/L
calcium chloride 2xH_2O	2,00	g/L
sodium sulphate	0,443	g/L

Konzenrat II_4 (500-fold-concentrated) (concentrate II_4)

(for R4 und WL3,4)

ammonium chloride	47,68	g/L
magnesium chloride 6xH_20	0,825	g/L
calcium chloride 2xH_2O	2,00	g/L
sodium sulphate	0,443	g/L

III. List of Figures

IV. List of Tables

V. List of Abbreviations

BOD5	5 day biochemical oxygen demand
const.	constructed
HSFCW	(Laboratory-Scale) Horizontal Subsurface-Flow Constructed Wetland
lab.	laboratory
obs.	observed
PFR	Planted-Fixed-Bed-Reactor

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